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A study of compensation flows in the UK

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ABSTRACT

The objectives of the study were to summarise the existing level of compensation awards below reservoirs, to assess the hydrological and biological aspects of compensation flow policy and to develop guidelines for setting compensation releases. The historical review of compensation flows identifies the major influences and legislative controls which have governed compensation flow policy since the early 19th century. A survey of current awards covered patterns of releases, their regional variation and the proportions of gross yield released. The practice of reducing compensation flows in extreme droughts by obtaining Drought Orders is illustrated using the 1984 drought. The influences of compensation flow releases on downstream flow regime and reservoir yield, are described together with a review of the possible effects of artificial flow regime on biology.

One of the main conclusions of the report is that the majority of current releases were set to satisfy river interests which no longer apply or were set in the absence of hydrological or biological information. The report concludes by presenting guidelines to assist in setting awards at new or existing reservoirs on a more rational basis and this is supported by a manual for estimating the seasonal variation in river flow at gauged and ungauged sites.

An appreciation of the scope of the report and the principal recommendations can be obtained from reading chapters 1 and 8.

PREFACE

This report describes the results of a study of compensation flows in the United Kingdom carried out by the Institute of Hydrology. The work was commissioned by the Department of the Environment under research contract No. PE.CD7/7/013. The opinions expressed and conclusions are those of the authors and are not necessarily those of the Department.

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The authors would also like to thank the following contributors to this report; Dr. J Sheail of the Institute of Terrestrial Ecology for the historical survey (described in Appendix A1 and summarised in Chapter 2), K. Tattersall for the case study of the Yorkshire Water Authority area (described in Appendix A2) and Dr. Armitage of the Freshwater Biological Association for the investigation of invertebrate communities below reservoirs (described in Appendix A4 and summarised in Chapter 6). Dr Crisp also of the Freshwater Biological Association provided advice on the fisheries aspects of the study described in Chapter 6 of this report. The Department of the Environment have supported earlier studies of "Invertebrate Communities" and "The Flow Requirements of Salmonids" at the Freshwater Biological Association and a Low Flow Study at the Institute of Hydrology. The results from these commissions have provided a valuable input to this project which has also made considerable use of the Surface Water Archive of discharge data held at the Institute. Finally we would like to thank David Gander for cartographical contributions to the study and to Sandra Smith for typing this report.

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1. SUMMARY

1.1 Introduction

The objectives of the study were to review the existing levels of compensation flows in the U.K. and develop guidelines for setting flows below impounding reservoirs. At the outset of the investigation it was recognised that individual compensation awards will always be based on a wide range of local factors and that a 'national standard' would clearly be inappropriate for reconciling the conflicting and varied demands on the river below the reservoir. However many existing awards were set by interests which no longer prevail, by 'rules of thumb' which developed in the absence of hydrological or fisheries information, or by the expedience of using local precedents which may no longer be appropriate. The approach of this study was to review the historical development of compensation flows, to summarise the existing range of release patterns and assess their influence on downstream flow regimes. A review of the effect of artificial flow regimes on the downstream freshwater biology was also carried out. These surveys together with discussions with the Water Industry were used to formulate guidelines for setting compensation awards.

The scope of the study was restricted to the problem of setting compensation flows below impounding reservoirs and not the more general problem of setting licences for all river abstractions. Furthermore, the main theme of the report is a hydrological survey and although the area of freshwater biology is considered, a number of other important subject areas such as water quality, temperature and sediment regimes were beyond the scope of this investigation. The term 'residual flows' is preferred by some authorities to encompass all discharges below abstractions on the grounds that no value judgement is made regarding the ability of the flow to truly 'compensate'. However, "compensation flow" is more widely used and was defined as recently as the 1976 Drought Act as "compensation water means water which any water authority or statutory water company are under an obligation to discharge into a river, stream or brook or other running water or into a canal as a condition of carrying out their undertaking".

In order to determine current interests which are considered and the practices for setting or modifying compensation flows, discussions were held with the U.K. water industry. Some organisations had recently reconsidered individual awards and were able to describe the process by which modified flow regimes were arrived at. Others considered that any advantages to the river or the net yield of a scheme would be offset by the negative publicity associated with changing a statutory compensation flow. There were no plans to review systematically all compensation flows in a given resource area although individual Authorities had revised specific awards or were in the process of investigating particular schemes as and when staff were available to carry out the work. There were no formalised procedures for reviewing compensation flows.

1.2 River Interests

The majority of reservoirs are releasing the same compensation flow as when the reservoir was first impounded. Appendix A1 describes a number of these schemes and details many of the interests which were considered when these flows were first set. These ranged from the early dominance of downstream industrialists anxious to maintain high flows for wool and cotton mills, to concerns about water quality associated with maintaining adequate dilution of domestic and industrial effluents and by the early 20th century to protecting migratory fishing interests especially in regions with major water transfer schemes to industrial areas. In setting compensation flows it was not possible to quantify many of the downstream flow requirements and this led to a judicious blend of 'horse trading', of using local precedents and 'rules of thumb', the most common of which was allocating one third of the gross yield to compensation flow.

TABLE 1.1 SUMMARY OF RIVER USES WHICH ARE CONSIDERED WHEN ASSESSING COMPENSATION FLOW REQUIREMENTS

Existing licence holders to abstract water for agriculture, industry and water supply
Dilution of point source effluents, river quality objectives, public health
Power generation - regard to daily and seasonal demands
Navigation - maintenance of adequate minimum depth and lockage
Riparian rights e.g. stock watering and household purposes
Migratory and coarse fish
Angling
Plant and invertebrate ecology - nature conservation
Amenity - canoeing, swimming, bank side recreation
Maintaining natural beauty.

Table 1.1 summarises the list of interests which had been considered when reviewing or setting compensation flows. Some of these can be expressed in discharge terms very easily, for example, the need to accommodate existing licence holders downstream who have historically relied on a compensation discharge to maintain their abstraction at low flows. Maintaining water quality presents more problems in determining an adequate compensation flow; although in terms of point source pollutants Regional Water Authorities have developed procedures which could be used to assess the effect of changing the flow regimes on the water quality downstream of effluent inputs. The effect of changing a compensation discharge on downstream water quality will be restricted to the river reach immediately below the dam and as the proportion of natural catchment area increases so will the effect on water quality diminish. In some industrialised areas of the Pennines, compensation water is a high proportion of the dilution afforded to industrial and domestic effluents. Despite the requirement for some very generous compensation awards having changed from the interests of mill owners to that of water quality, the need for some of these high discharges will remain until the treatment of effluent discharges is improved. A multi-disciplinary approach to the determination of compensation flow is very necessary. This is particularly important when estimating the benefits of improved effluent treatment to downstream water quality and fisheries and, if compensation flows can be reduced, to the yield of upstream water supply schemes. Water quality models ranging from simple mass balance calculations to statistical or time series simulations of flow and quality are available for addressing these issues. Although a review of water quality modelling techniques is not presented in this report, where water quality issues are critical it is essential that detailed site specific studies are carried out. For example, Thames Water Authority (1984) have considered the implications of altering the control rules of the prescribed flow of the R. Thames at

Teddington on the ecosystems of the Lower Thames and its tidal estuary. This detailed study made use of separate mathematical models of the river and estuary to predict changes in water quality resulting from alterations in the flow regime. Biologists then evaluated the implications for river ecology.

Although the result of modifying compensation releases on effluent dilution may be assessed, it is difficult to determine the effect on river biology even in unpolluted rivers. In addition to discharge, the chemistry and water temperature downstream of the reservoir may be influenced by a change in operating policy which in turn will affect plant and invertebrate ecology and fish populations. The effects of these alterations will be at a maximum near the dam and reduce as natural inflows increase further downstream. Chapter 6 describes some of the factors which must be considered when the fisheries aspects of compensation flow policy are being addressed. For example prolonged periods of low flow may result in siltation of river gravels reducing intragravel flow, resulting in poor salmonid egg survival rates due to reduced oxygen supply. The requirements for other stages of fish development - spawning, downstream and upstream migration must also be considered, as well as flow conditions suitable for angling success. However, relationships between both water quality and quantity and the life cycle of migratory and coarse fish remain elusive and little information is available on which to base a decision on the optimum compensation flow.

1.3 Historical background

Chapter 2 of this report describes the historical background to setting compensation awards using evidence from Parliamentary Select Committees for a number of reservoir schemes completed in the U.K. in the 19th and 20th centuries. The earliest reservoir schemes were designed to supply water to maintain navigation on the expanding canal system and Acts of Parliament were required to protect existing users of the river below each reservoir. The same approach was used in granting powers for subsequent water supply reservoirs and the influential position of industrial interests, particularly mill owners, dominated the discussions in setting these early compensation flows. For example, a number of Acts of Parliament stipulated zero compensation flows at weekends when mills were not working in order to maximise the flow during the working week. It was not until the close of the 19th century that consideration was given to other water uses such as fisheries and dilution of domestic and industrial effluent. The Elan valley scheme promoted in 1892 and the Haweswater scheme of 1919 were the earliest to consider seriously the problem of flow regulation and fisheries. In the latter case this provided for the periodic release of freshets in addition to a minimum discharge.

There have been several attempts to provide general guidelines for setting compensation flows. The first of these was proposed by Hawksley to the Royal Commission on Water Supply (1869). He suggested that the starting point for negotiation should be that two thirds of the gross yield should be used for supply purposes and the remainder for compensation flow. Hawksley's concept that downstream flows be related to reservoir yield rather than to the characteristics of the receiving stream was the basis of many schemes. It was not until 1930 that a technical subcommittee of the Ministry of Health recommended that both the natural character of the receiving stream and the use of the river should be considered. More recently the Water Resources Act of 1963 and the Water Act of 1973 were introduced and a more coherent approach to assessing the environmental impact of new and revised schemes has developed. However, local precedents and 'rules of thumb' continue to be an important aspect of setting compensation flows and the majority of awards have not been reassessed since they were introduced.

1.4 Compensation releases and effects on flow regime

One of the main objectives of the study was to provide a summary of the existing compensation flows which have been determined for reservoirs in the U.K. Chapter 3 presents the results of this study. Information was collected from the reservoir operator on the details of the type of reservoir, compensation releases, the net and gross yield, date of impoundment, capacity and upstream catchment area for over 500 reservoirs in the U.K. Small reservoirs with capacities of less than 500 Ml or catchment areas of 5 km^2 were excluded from the final analysis which was based on 261 reservoirs. 60% of the remaining reservoirs had catchment areas of less than 20 km^2 with only 11% being greater than 100 km^2; 40% of reservoirs had capacities less than 2000 Ml with only 15% having capacities greater than 20,000 Ml. Details of all these reservoirs are listed in Appendix A3.

Three main patterns of compensation release were identified. Some 70% of reservoirs release a constant discharge throughout the year although some of these also release artificial floods or freshets. Other reservoirs have seasonally varying compensation flows with a summer maximum below all but one of the reservoirs. The third type of release is where discharges must be maintained at a particular threshold some distance below the dam rather than at the dam site itself.

In order to compare compensation flows between different schemes the compensation discharge was expressed as a percentage of the natural mean daily flow at the same location. The average release of the 261 reservoirs for which data were available was 16% of the mean flow (18.6% if reservoirs with zero compensation releases are excluded). Chapter 3 details the variation in compensation flows between different schemes and summarises the regional differences in flows. This shows relatively generous awards in the areas now administered by North West and Yorkshire Water Authorities and very low awards in south west England and Northern Ireland. An analysis of the historical trend of compensation flows indicated that there were high settlements for many of the 19th century water supply schemes in industrial areas and generally lower awards since 1920.

An analysis of the change in flow regime following impoundment is described in Chapter 4. This was based on flow records below 29 reservoirs. Mean discharge was on average reduced to 55% of the natural flow with a maximum reduction to 12% of the natural mean discharge. A comparison of flow duration curves before and after impoundment and the use of naturalised flow data enabled the change in discharge for given exceedance frequencies to be calculated. In each case discharge was standardised by the pre impoundment natural mean discharge. The greatest reduction in discharge is between the 10 and 90 percent frequencies with the median discharge being reduced to 43% of the natural flow. Although the average 95 percentile discharge for all 29 reservoirs showed no significant change before and after impoundment, wide departures from maintaining the natural low flow do exist. In view of this the 95 percentile natural discharge was estimated for a further 155 sites and compared with the statutory compensation flow. This study showed a similar wide variation in flows between individual schemes with a mean compensation flow of 17.7% and the mean Q95, 14.0% of the natural mean discharge.

1.5 Seasonal compensation flows and effect on reservoir yield

The survey of compensation flows indicated that many schemes, particularly where fishing interests were dominant, had seasonal variations in compensation flow usually with the winter discharge being half or one third of the summer flow. Discussions with the water industry supported the concept of seasonally varying discharges and highlighted the need for more information on the natural seasonal variability of flows in order to assist in setting compensation flows. This could be readily estimated where flow data were available at or near the site of interest but there was an obvious need to develop procedures for estimating seasonal flow duration curves at ungauged sites. The results of this work are summarised in Chapter 7 and an estimation manual is included as Appendix A6.

If an existing reservoir operating policy with a constant compensation flow is changed to one with a lower compensation flow, then the net yield of the reservoir will increase by the reduction in compensation flow. If a constant compensation flow is changed to a seasonal flow then the net yield of the reservoir will also change even if the total volume of compensation water remains unchanged. The effect on the net yield of the reservoir will depend on the ratio of, for example, winter to summer discharge, on the volume of storage and the initial reservoir yield. Chapter 5 of this report summarises the effect of introducing seasonally varying compensation flows on reservoir yield. The results are illustrated for a simple direct supply reservoir with only two different compensation flow periods (summer and winter), although more complex reservoir systems and compensation patterns can be easily simulated.

1.6 Guidelines for setting compensation flows

The historical review of compensation flows and the survey of current releases suggest that many reservoirs continue to provide compensation flows which were determined by industrial and political constraints which no longer apply. Furthermore the majority were awarded when there were little or no hydrometric data to describe differences in catchment hydrology and little knowledge of the impact of impoundments on downstream fauna and flora. Although environmental impact studies of new reservoirs have increased since the 1963 Water Resources Act, the use of local precedents has remained an important criterion for setting compensation flows. This would suggest that a review of current releases, particularly below older reservoirs, is warranted especially when water resource developments or changes in operating policy are being considered. However, the objective of such a review should not be restricted to that of improving the yield of the reservoir but should include improvements in water quality, fisheries and general amenity.

Recommendations for setting compensation flows are presented in Chapter 8 and cover three main areas. The first relates to defining the length of river which is influenced by compensation releases and identifying the location and importance of river interests which are affected. It is helpful to distinguish which aspects of the flow regime are critical. For example the dilution of effluents will be discharge dependent but some amenity interests may be level dependent in which case river restoration schemes may enable adequate levels to be maintained with very low discharges using weirs. The second area concerns a number of technical advances which have been made since the majority of compensation flows were set. These include developments in hydrology, freshwater biology and in the field of instrumentation and control which enable greater flexibility of operation to be implemented. The third area relates to institutional arrangements. A more flexible response to compensation flow provision should be developed which includes the periodic review of compensation releases.

1.7 Further research requirements

The primary area where further research work is required is in the relationship between changes in flow regimes and downstream fauna and flora. In this area a multi disciplinary approach is essential embracing hydrology, hydraulics, fluvial geomorphology, water quality modelling, plant and invertebrate ecology, fisheries biology and nature conservation. Two priority research areas have been identified. The first is in developing quantitative relationships between freshwater biology and the physical and chemical variables at a scale appropriate to the river reach. The second is to develop practical management techniques for evaluating the biological response to changes in river discharge. This requires the development of simulation models which will link the changes in river hydrology and hydraulics to the changes in freshwater biology. Such models should enable the impact of different compensation flow policies to be assessed and permit the performance of proposed restoration schemes to be evaluated. Specific research is urgently required to evaluate the benefits of the continuing practice of releasing artificial freshets to aid salmon migration. This could include the collation of fish count data onto a central archive and developing simple empirical relationships with river flow. Although individual analyses of these data have been carried out for specific rivers there would be considerable benefits from a national study.

The problem of setting compensation flows is part of the wider problem of residual flows in rivers. The setting of licences for river abstraction requires the same modelling techniques for assessing the environmental impact of proposed water resource schemes. For abstractions in the lower river reaches the influence on the estuary must also be considered. A summary of the changes in the natural flow regime and a national survey of existing abstraction schemes would be a useful contribution to this area of work.

2. HISTORICAL REVIEW OF COMPENSATION FLOWS

2.1 Introduction

Before studying existing compensation flows it is essential to appreciate how the concept of [illegible]sation water was first perceived and how it has subsequently bee[illegible] to river management. Compensation releases at some reservoir[illegible] over 100 years ago, so it is important in considering any revisions [illegible]erstand how and why the releases were originally set and the legislation operating at that time.

This chapter is essentially a summary of dominant influences and legislation affecting the setting of compensation flows. For a detailed historical appraisal of the development of compensation water and legislation up until 1945, the reader is referred to Appendix A1. Appendix A2 illustrates different ways in which compensation flows have been revised, with case study examples from the Yorkshire Water Authority area.

Appendix A1 shows by reference to a wide variety of agreements reached over levels and methods of compensation discharge in UK, how precedents for setting compensation flows were established and subsequently applied to schemes in other areas. The search for a coherent approach to assessing compensation flows is examined. Legislative procedures in Scotland have developed separately to England and Wales, and a detailed case study of the development of the Edinburgh supply schemes is also presented (see also Sheail 1985).

2.2 Compensation flow policy 1800-1945

Up until 1945, in England and Wales all compensation releases had to be set by individual Acts of Parliament in the form of a Private and Local Bill. During the late eighteenth century, Acts were required for canal construction, outlining which streams were to be diverted and how other stream users were to be protected from injury. Water undertakers had to follow a similar procedure. Most early compensation awards related to water supply reservoirs built in the Pennine valleys a short distance upstream of towns where the developing cotton, wool and steel mills required water for power production and processing purposes. Before authorising impounding schemes, Parliament was always vigilant in ensuring that the interests of industrialists and other riparian owners downstream were protected. The millowners were for a long time the dominant influence in setting compensation flows and this led to very generous releases, sometimes made only during mill working hours with zero releases at other times.

Belmont reservoir in Lancashire was one of the first constructed solely to provide water to the millowners, in compensation for the use of a spring for supply purposes. Under the 1824 Bolton Waterworks Act the millowners ensured a generous compensation provision to the mills downstream. The 1847 Waterworks Clauses Act stipulated for the first time that compensation provisions had to be made to anyone injuriously affected by diversion of streamwater or impoundment. Although this Act made explicit provision for pecuniary compensation, in practice compensation was made by a release of water from a compensation or dual purpose reservoir. The first attempt to provide guidelines for setting compensation flows was provided by Hawksley to the Royal Commission on Water Supply (1869). [illegible] suggested that, as a starting point for negotiation, a third of the reliable yield should be released as compensation water with the rest going to supply. This 'rule of thumb' was widely adopted for many schemes. The millowners, however, continued to dictate how compensation water should be released until 1888, when the Halifax Corporation Waterworks Act set the precedent for releasing compensation water as a constant discharge rather than an intermittent flow. This was to prevent the deleterious effects of a zero flow on the river at a local beauty spot, and marked the start of environmental awareness of the effects of different compensation policies. It was followed by other similar Acts e.g. Bradford Waterworks Act in 1890.

The creation of the West Riding County Council (Local Government Act 1888) proved to be significant for river conservation. The Council, in not being responsible for water supply and sewerage functions, was able to take a more independent view of the environmental consequences of proposed releases. The Council were successful in urging Parliament to make a Standing Order instructing Select Comittees to insist that compensation water be discharged as a constant flow.

The period up to 1920 saw the passing of a series of individual Acts to authorise the construction of some major water resource schemes in which industrial interests did not dominate. The Elan Valley scheme promoted in 1892 and the Haweswater Scheme of 1919 were the earliest to consider seriously the problem of flow regulation and fisheries. The latter case allowed for the periodic release of freshets in addition to a minimum discharge. The 1921 Water Power Resources Committee criticised methods in use for assessing compensation water which were based primarily on the estimated yield of the catchment. They argued that greater attention needed to be paid to the character of flow in the natural river and to the requirements of all riparian users. This led to the appointment of a series of other committees to study compensation flows, although new legislative procedures were not introduced until 1945. One such committee, a Technical Subcommittee of the Ministry of Health advisory committee in 1930, devised a formula for assessing compensation releases and criticised previous awards as being too generous, leading to formulation of a draft White Paper on the problem. However this was rejected by a Joint Committee in 1936, on the grounds that they doubted that Parliament could have been so seriously in error when compensation awards were fixed initially. The Committee attributed any unsatisfactory awards to inadequate rainfall and runoff information.

2.3 Legislation in England and Wales post 1945

2.3.1 Water Act, 1945

This Act did not change the situation for existing reservoirs (since releases set under a previous Act could only be altered by a new Act not an Order), but for new schemes it made possible the acquisition of rights to take water by Order rather than by Act of Parliament. Section 26(5) stated that in assessing compensation water, the Minister must consider

(i) the character and flow of the stream
(ii) the extent to which the stream is or <u>may in future</u> be used for industrial purposes, fisheries, water supply, transport or navigation.
(iii) the effect on land drainage, any canal or inland water of any alteration in flow.

Section 10(2) of the Third Schedule of the Act stipulated that compensation water should take the form of a uniform and continuous flow during every day of 24 hours. This was a response to the earlier practice of millowners cutting off compensation altogether from 12 noon on a Saturday to 6 am on a Monday.

The possibility of obtaining a private Act remained, however, and largely for technical reasons relating to land acquisition, this continued to be the preferred approach for many authorities. The two alternative procedures therefore continued in parallel.

2.3.2 Water Act, 1958

Section 1 of the Water Act 1958 made it possible in time of drought to apply for a 'Drought Order' reducing, for a period not exceeding 6 months, the amount of compensation water to be discharged from any particular reservoir. These Drought Order powers were extensively used during the drought of 1959 and, indeed, in many dry summers thereafter. Until the passing of the Water Resources Act 1963 there was still no simple way for a water undertaking to rid itself permanently of an excessively onerous requirement to discharge compensation water.

2.3.3 Water Resources Act, 1963

This Act set up 26 new River Authorities to cover England and Wales replacing the former River Boards whose duties they took over. The Act also brought about a fundamental change in the law insofar as it made rights to impound and abstract water obtainable by licence from the River Authorities. A River Authority could impose conditions on the licence including compensation provisions. Virtually all rights to abstract water were made licensable under the Act - including those rights acquired by private Act, referred to as "alternative statutory provisions". Procedure was also laid down for 'varying' a licence and it became possible to increase or reduce the quantity of water authorised to be abstracted or to vary the conditions imposed on the licence.

This facility to vary an abstraction licence was also applied to the provisions of the private Acts. Section 48 of the Act, broadly stated, made it possible to vary the compensation provisions of an 'alternative statutory provision' (i.e. a private Act) by the same procedure as required under the Act for the variation of an ordinary abstraction licence. This put the power to determine compensation requirements firmly in the hands of the River Authorities, though the initiative for altering compensation provisions would be expected to come from the water supply authorities as the holders of the licences. The Secretary of State would still reserve powers to review any licence and decide on licences where objections had been raised.

2.3.4 Water Act, 1973

This Act created ten Water Authorities in England and Wales which absorbed both the former water supply authorities (excluding water companies) and the River Authorities. The new Water Authorities thus acquired the rights, responsibilities and duties of the River Authorities. A Water Authority (like a former River Authority) wishing to grant itself a licence or to vary one of its existing licences, is required to advertise its proposals, receive any representations against them, and then to put them before the Secretary of State who may then allow the Authority to grant itself the licence or variation proposed or altered, as he sees fit. Where variation of an alternative statutory provision is involved, the Secretary of State varies the actual sections of the Private Act in accordance with the provisions of Section 133 of the 1963 Water Resources Act.

2.3.5 The Drought Act, 1976

This Act enlarged the scope for obtaining emergency powers for Water Authorities to abstract water and control water use, but left the provision for temporary reduction in compensation water discharge virtually unchanged since the Water Act, 1958.

2.4 **Legislation in Scotland post 1945**

Legislation has developed separately here from that in England and Wales, with the River Purification Boards being responsible for 'river' interests and Regional Councils responsible for 'supply' interests. The determination and provision of compensation water to rivers in Scotland is still governed by the Water (Scotland) Act of 1946. Hydro-electric schemes are controlled separately by the Hydro-electric Development (Scotland) Act, 1943.

Under the 1946 Act the Secretary of State for Scotland must promote the conservation of water resources and maintain adequate water supplies throughout Scotland. He has no powers over private rights to abstract water, which are governed by common law. For impoundment schemes, the Secretary of State for Scotland must ensure that adequate compensation provision has been given, or when obtaining rights by compulsory order must prescribe the amount of compensation water. In assessing the volume of water, he should follow the same considerations as outlined in the Water Act 1945 for England and Wales. The section of the 1946 Water Act (Scotland) giving the Secretary of State power to amend compensation water provisions was inadvertently repealed by the 1967 Water (Scotland) Act, but was restored in the Local Government (Scotland) Act, 1973. The Secretary of State may modify compensation provisions in local enactments by Order and temporary reductions or modifications are possible under the Water Act 1958 (this no longer operates in England and Wales).

2.5 **Drought Orders**

The Drought Act 1976 enables Water Authorities and undertakers to temporarily change or be relieved of their statutory obligations during times of drought. The emergency powers, contained in different sections of the 1976 Act and applied for in the form of a Drought Order, include the following;

(i) Changing amount of water released as compensation.

(ii) Altering conditions on abstraction licences, and bringing new sources into operation.

(iii) Restricting the use of water for non essential purposes including car washing and swimming pools. In more extreme circumstances recourse may be made to directly limit usage by the introduction of standpipes, rota cuts, etc.

Drought Orders are of widespread and accepted use during prolonged periods of low flow. The procedure for applying for a Drought Order can be lengthy and includes the following steps.

(i) The initiative for a Drought Order application comes from the Water Authority, based on their assessment of the severity of the drought and adequacy of supplies. Each application is accompanied by supporting data and may take 1-2 weeks to prepare. If compensation flows are being altered discussions will normally take place between

water resource and fisheries staff before a new level of compensation flow is set.

(ii) All applications must be advertised both locally and in the Government produced London Gazette and problems in reproducing an accurate advertisement can lead to delays (Welsh WA 1985). The 7 day period for objection commences with the publication of the last absolutely correct notice, so the advertising procedure can take at least 2 weeks.

(iii) The application and any objections received are considered by DOE for England and the Welsh Office in Wales, and a recommendation made to the Secretary of State. A public inquiry hearing must be held prior to this to hear objections, unless the Secretary of State dispenses with a public inquiry/hearing in accordance with schedule 3(1) of the Act.

Therefore, in all, there is normally at least a 7 week delay between a Drought Order application first being considered and finally made (Welsh WA 1985). Once an Order has been approved it is normally implemented the next day, and until the expiry date given on the Order. Thus Drought Orders have to be applied for in the early part of a drought, before the full severity of the situation may have become apparent. It is sometimes necessary to apply for a second Order at a later date, revising the size of compensation flow reduction or expiry date. This time delay is one of the aspects considered in section 3.6 in an analysis of Drought Orders made during the 1984 drought to reduce compensation flow.

Welsh WA (1985), in their report on the 1984 drought, found this timing problem to be particularly acute where reservoirs have a rapid rate of drawdown, such as in river regulation schemes. As Welsh WA point out, at some reservoirs in N.Wales, lead times for application of compensation reductions cannot be achieved unless made while the reservoir is still full. Thus, if the drought does not develop many Orders may never be implemented or conversely Orders may need to be superceded by more drastic measures; either way a great deal of time and effort is involved. The advantages of greater flexibility of operation linked to control rules have been described by Lambert (1985) with reference to the 1984 drought. The satisfactory operation of the Dee system in environmental and supply aspects were the direct result of implementing pre planned control rules. This contrasted with the problems experienced in many other schemes where Drought Orders were applied for during the 1984 drought, but at a time when there was little alternative to introducing severe reductions to supply, the consumer and the river.

There is therefore clearly a need for establishing more flexible statutory powers for water undertakers, with provision for changes during droughts. Welsh WA estimate that some 40% of Orders applied for in their area could have been avoided if licences allowed for drought conditions. They point out two major difficulties; firstly the problem of defining when a drought exists, secondly the delay involved as each licence variation could take 2-3 years to implement. The Secretary of State must consider objections, and be certain that any measures could only be used in a drought, and not when a reservoir is emptied as part of the standard procedure in conjunctive schemes.

The Water Authorities Association (1985) has considered how well these Drought Order procedures operated during the 1984 drought. They agree with the need for greater flexibility, but felt that some authorities had been able to develop procedures to do this under existing legislation. They therefore recommended that no amendment to the provisions under Section 1(3), Drought Act 1976, relating to prescribed flows and compensation releases from reservoirs was necessary. They felt generally that, although the Drought Act, 1976 was a considerable improvement on previous legislation, it still had short-comings which could be remedied by amended legislation. The report suggests that Water Authorities should have more freedom to impose restrictions on the non essential use of water at their own discretion; the more serious powers, such as those affecting peoples' livelihood, should however remain subject to Ministerial approval. The Water Authorities called for modifications to the advertising procedures when applying for Drought Orders, since, as noted earlier, these may introduce unnecessary delays and difficulties. In addition they would like to remedy inconsistencies between those powers in a Drought Order relating to renewal and those relating to extension of existing Drought Orders.

3. SURVEY OF COMPENSATION FLOWS FROM UK RESERVOIRS

3.1 Introduction

One of the objectives of this project was to provide a summary of existing statutory compensation flows from UK reservoirs. It was hoped this would enable the revision of existing awards and the setting of new ones to be considered in a wider context. It was clear from the preceding chapter that the basis upon which past compensation flows have been awarded has not been uniform. By the more detailed analysis contained in this chapter one hoped to identify the development of a more consistent approach for setting compensation flows in recent years, and any regional differences in awards. Such inspection could reveal, for example, how widespread was the practice of releasing approximately one third of the reliable yield for compensation purposes (see Chapter 2) or might demonstrate that it was merely a starting point for negotiation rather than the final figure.

Reservoir data, including the nature and size of compensation releases, is not routinely archived in the UK. Risbridger (1962) provides a limited overview, summarising data from reservoirs and expressing compensation flows as a proportion of the yield. The largest UK reservoirs with capacities in excess of 10,000 Ml are listed by Rodda et al., (1976) but no compensation flow details are recorded. Since there was no single source of data on reservoirs of all capacities, a major part of this project was the collation of information on existing compensation release policies and other relevant reservoir details, from all possible sources. This information is of varying degrees of complexity. Since many compensation flows were set over 100 years ago, the data tend to be piecemeal and of varying reliability depending on their source. This information was stored on a computer archive for ease of access and analysis.

The bulk of the data was collated during a series of visits to the reservoir operators, namely the regional Water Authorities in England and Wales, Regional Councils in Scotland and the Water Services Department of DOE in N. Ireland. Discussions also took place with River Purification Boards, DOE, and Government research organisations. These are listed in full in Table 3.1. There was considerable variation in the availability and ease of access of data within these organisations. Engl00 forms, the returns of water undertakers to the Ministry of Housing and Local Government from 1966 to 1973, were a useful source of data. These forms give details of the area and population supplied, water supply sources, namely impounding and service reservoirs, boreholes and springs and also water treatment works. The NSHEB provided details of major hydroelectric schemes in Scotland and copies of constructional scheme reports outlining the often complex compensation agreements. Reference was also made to parliamentary orders, and published technical reports on some recent schemes.

3.2 Computer archive

3.2.1 Reservoir and compensation flow variables

A reservoir archive (Appendix A3) was developed which summarised details of all impounding reservoirs in England, Scotland and Wales, for which data were made available by the operating authority. Although not included [illegible] in archive, details of reservoirs in Northern Ireland are described separately in section 3.5. The large number of sources of data

TABLE 3.1 LIST OF ORGANISATIONS CONTACTED

Anglian Water Authority
Central Regional Council
Central Scotland Water Development Board
Clyde River Purification Board
Cuthbertson and Partners
Dept. of Agriculture and Fisheries, Pitlochry, Scotland
Dept. of the Environment, London
Dept. of the Environment, N. Ireland
Freshwater Biological Association, Wareham & Teesdale Unit
Fisheries Consultants - N. Graser
D. Mills (Edinburgh University)
Forth River Purification Board
Highland River Purification Board
Institute of Terrestrial Ecology, Edinburgh & Cambridge
Lothian Regional Council
Nature Conservancy Council
North East River Purification Board
North West Water Authority
North of Scotland Hydroelectric Board
Northumbrian Water Authority
Scottish Development Department
Severn Trent Water Authority
Solway River Purification Board
Southern Water Authority
South West Water Authority
Strathclyde Regional Council
Tay River Purification Board
Tay Salmon Fishing Company
Tayside Regional Council
Thames Water Authority
Tweed River Purification Board
Welsh Water Authority
Welsh Office
Wessex Water Authority
Yorkshire Water Authority

and its rather inaccessible nature precluded making a fully comprehensive list. Some reservoir types, for example pumped storage reservoirs with minimal natural catchment areas and natural lakes, (except those like Haweswater, where the ponding level has been artificially raised by a dam) were excluded at the outset. This resulted in there being no data for some areas of the country eg. Thames WA. The archive includes reservoirs of small capacity, those with insignificant compensation and supply releases, those built solely for supply purposes and others where available information is sparse. In total, information was collected on 552 reservoirs. It is hoped that the archive will provide a source of data useful outside the scope of the present study and for this reason reservoirs have been included in the archive where information on compensation flows are missing or available only in part.

The reservoir variables recorded are listed in Table 3.2, with more detailed definitions and methods of calculation given in Appendix A3, Table A3.1. Each reservoir has been assigned a reference number, (eg. R62004) which groups reservoirs under hydrometric area and signifies those which are operated together. Reservoirs are defined by their usage (TYPE); namely regulating, pumped storage, hydroelectric, 'compensation only' and direct supply reservoirs. The latter category is split into those reservoirs with zero releases to the river downstream ie. 'supply only' and those with compensation releases ie. 'supply and compensation' reservoirs. For dual purpose schemes, eg. reservoirs with both a supply and regulating function, it is the function which has the greatest influence on downstream river flows which is recorded.

Both the flow rate in Ml/day and temporal pattern of compensation releases are recorded (Table 3.2). A distinction is made between constant and variable releases, and between releases monitored at the dam site and those made to maintain a specified flow downstream. At each compensation or maintained flow location, compensation releases are compared with the natural flow regime. The natural average daily flow in Ml/day (ADFLOW) is estimated from the catchment area, long term rainfall and evaporation data derived by map analysis (see Table A3.1). The natural drainage area of each reservoir has been used and is defined to be the catchment area to the dam site, or where applicable to the 'maintained flow' point some distance downstream. At many reservoirs, additional runoff is contributed from outside the natural catchment by a system of catchwaters, and this is reflected in the figure for total catchment area. In all cases, reservoir variables, such as NATAREA, TOTAREA and ADFLOW, refer to exactly the same location as compensation flow details. A full description of the coding of compensation flows is given in Table A3.1.

3.3 Analysis of reservoirs

3.3.1 Introduction

It was decided to base analyses of compensation flows on a subset of larger reservoirs where a significant impact on downstream flows would occur. The criteria for inclusion in this subset were that the reservoir had to exceed 500 Ml in capacity, or if capacity figures were unavailable the drainage area had to exceed 5 km^2. In addition, information on either the amount of compensation release or method of release had to be available. 'Supply only' reservoirs located upstream of 'compensation only' reservoirs were also excluded, as the compensation reservoir was taken to represent the whole system. This left a subset of 261 reservoirs, identified on the reservoir archive listing in Table A3.3 and Table A3.4 by **. It should be noted that all analyses, tables, figures and discussion relate to this subset of 261 reservoirs. It is believed that they provide

TABLE 3.2 RESERVOIR AND COMPENSATION FLOW VARIABLES

Variable name	Definition	Units
NUMBER	6 digit reference number assigned to each reservoir, and linked to hydrometric area	-
NAME	Name of reservoir	-
GRID REF	Grid reference of dam site	-
OPERATOR	Name of operator	-
AUTHORITY	Name of regional water authority - Scotland treated as a single area	-
TYPE	8 category code to denote type of reservoir	-
DATE	Date of impoundment	-
NATAREA	Natural catchment area draining to dam, or in case of maintained flows, to the maintained flow point	km^2
TOTAREA	Total catchment area - includes drainage area of catchwaters in addition to natural catchment area	km^2
NYIELD	Net yield or firm quantity available for supply after making provision for compensation	Ml/day
GROSSCAP	Gross capacity	Ml
NETCAP	Net capacity - excluding dead water storage below drawoff points	Ml
ADFLOW	Natural average flow for same location as compensation flows - namely the dam site or maintained flow point	Ml/day
COMPCODE	18 category number code denoting nature of compensation releases. Releases at the dam site are denoted by a single digit code; maintained flow points by a 2 digit code.	-
COMPFLOW	Compensation flow at the dam or maintained flow point, released according to COMPCODE	Ml/day

a representative picture of the reservoir types and release policies used in the UK. However, despite attempts to make the reservoir data as complete as possible some values are missing. Therefore the number of reservoirs used in individual analyses will vary and may be less than the complete set of 261. In addition details of 15 reservoirs were collated from N. Ireland and these were analysed separately in section 3.5. The location of all reservoirs studied is shown in Figure 3.1.

3.3.2 Reservoir data

Reservoir type

The number of reservoirs of a particular type are listed in Table 3.3 and are graphically illustrated in Figure 3.2. It should be noted that this refers to the current function of the reservoir which has the greatest influence on the river downstream and does not imply that this has been its function since impoundment. Most reservoirs on the archive subset are of a direct supply type (163 out of 261). Of these, 147 release compensation water and 16 ('supply only' reservoirs) do not. Reservoirs constructed solely for hydro-electricity generation (30 reservoirs on the archive) are all located in Scotland. Pumped storage and regulating reservoirs are fairly equally represented on the archive.

Only 20 reservoirs were constructed solely for the purpose of storing compensation water. As discussed in Appendix A2, there are two different types of 'compensation only' reservoir. A distinction is made between those compensation reservoirs where the liability to release water is limited to the compensation reservoir and those reservoirs where liability to release water extends to upstream supply reservoirs. Compensation reservoirs tend to be concentrated in certain parts of UK, namely Lothian and Strathclyde areas of Scotland and the Pennine areas of Yorkshire and NW England. Most were constructed in the late nineteenth century, and they are located in the important industrial areas of that time.

Date of impoundment

The age distribution of the reservoirs included in the analysis is summarised in Figure 3.3. This shows an increasing rate of construction from 1850 to 1975, although current trends show a decline in the number of new reservoir schemes. Figure 3.3 also illustrates a gradual change in the type of reservoir. 'Compensation only' reservoirs were constructed during the period 1825 to 1925, and in particular from 1840-1880 due to the influence of the owners of cotton and woollen mills. Since 1950 pumped storage and regulating reservoirs have become more prevalent. The apparently early introduction of regulating reservoirs and pumped storage reservoirs is rather misleading, since many reservoirs built at that time have since undergone a change of function, often from supply to river regulation. Only the current function of the reservoir is recorded.

Capacity

Figure 3.4 emphasises the wide span of reservoir capacities, in excess of 500 Ml, included in the data set. 40% are less than 2000 Ml capacity and 15% are in excess of 20,000 Ml, with a mean capacity of approximately 16,000 Ml. The largest reservoirs, such as L. Quoich (R6202) and L. Fannich (R4501) are the outcome of raising the level of natural lakes for hydroelectric generation in Scotland; other large reservoirs were built for regulating and pumped storage purposes.

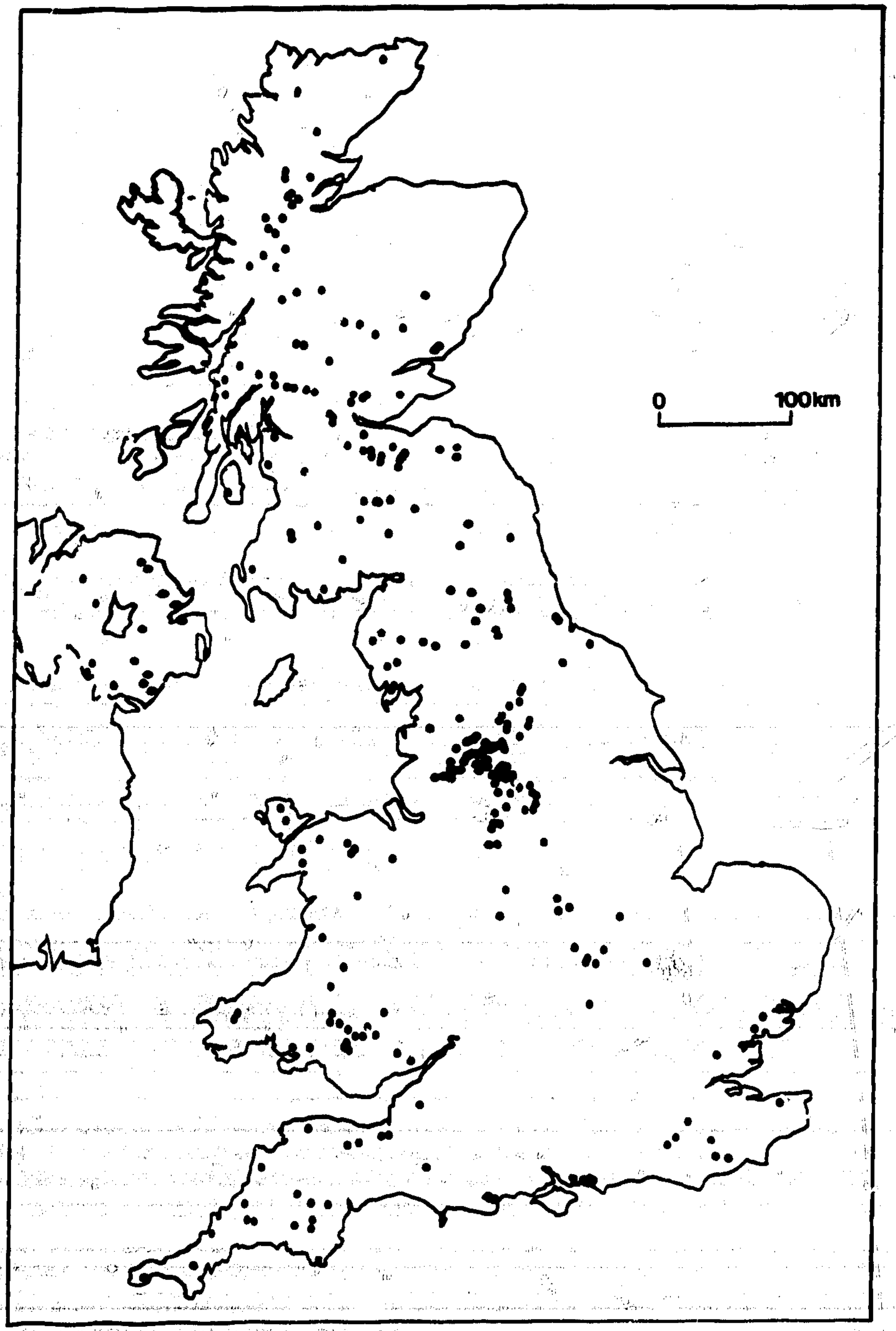


Figure 3.1 Location of reservoirs

TABLE 3.3 TYPES OF RESERVOIR

			Number
Direct supply	(a)	supply with compensation releases	154
	(b)	supply with no compensation release	16
Compensation only			20
Regulating			20
Pumped storage			18
Hydro electric			30
Other - canal, feeder/industrial			3
			261

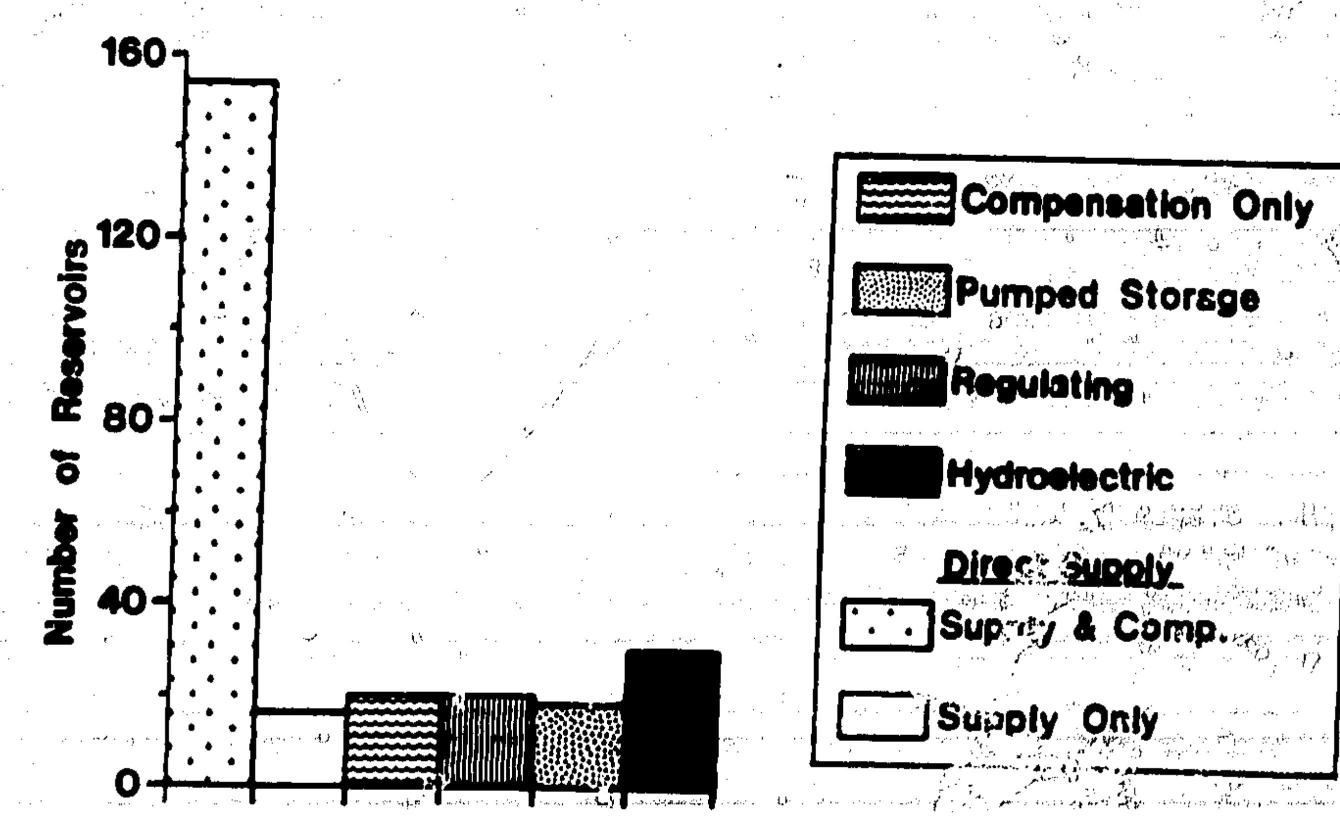


Figure 3.2 Reservoir types

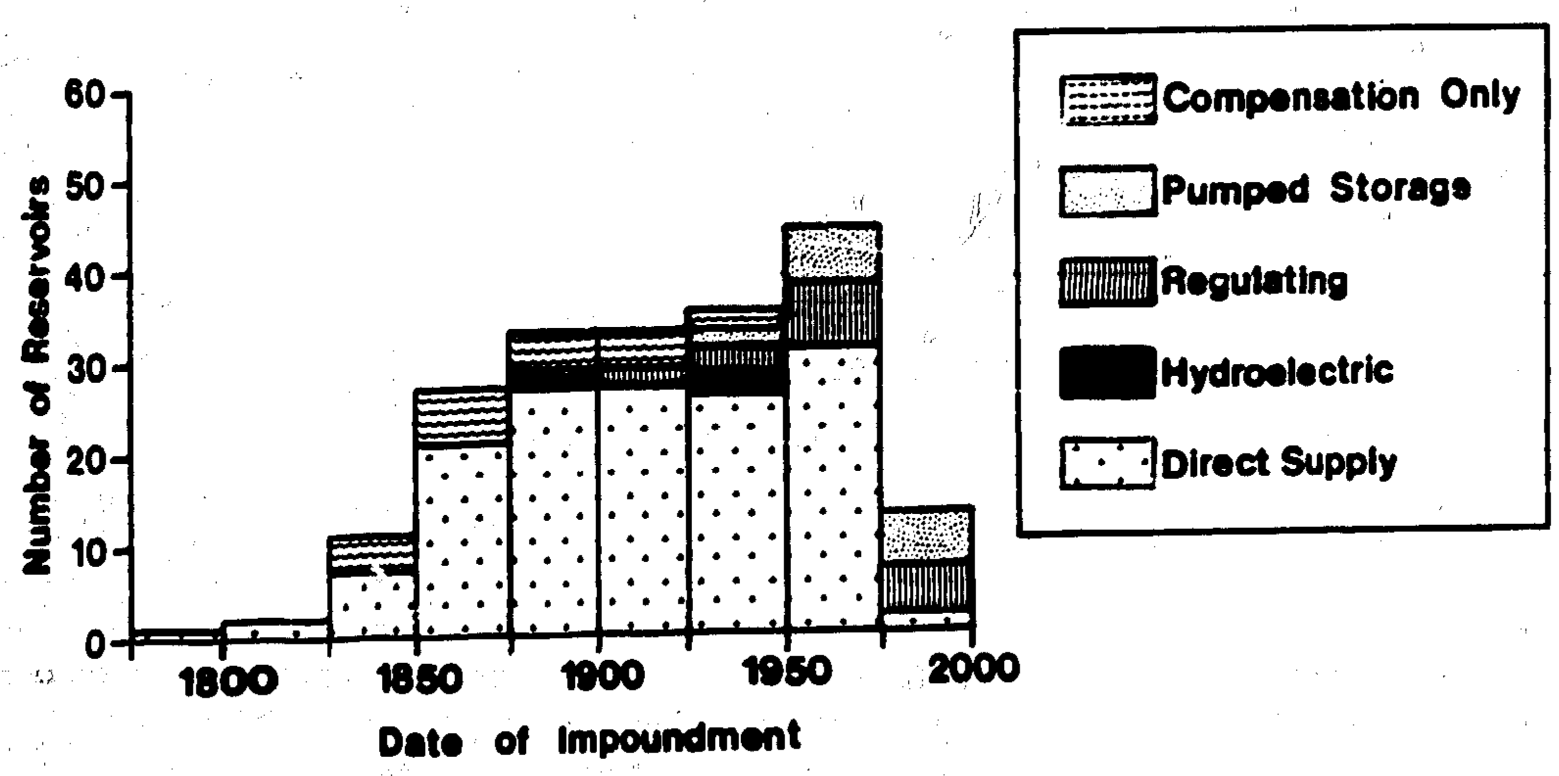


Figure 3.3 Dates of reservoir impoundment

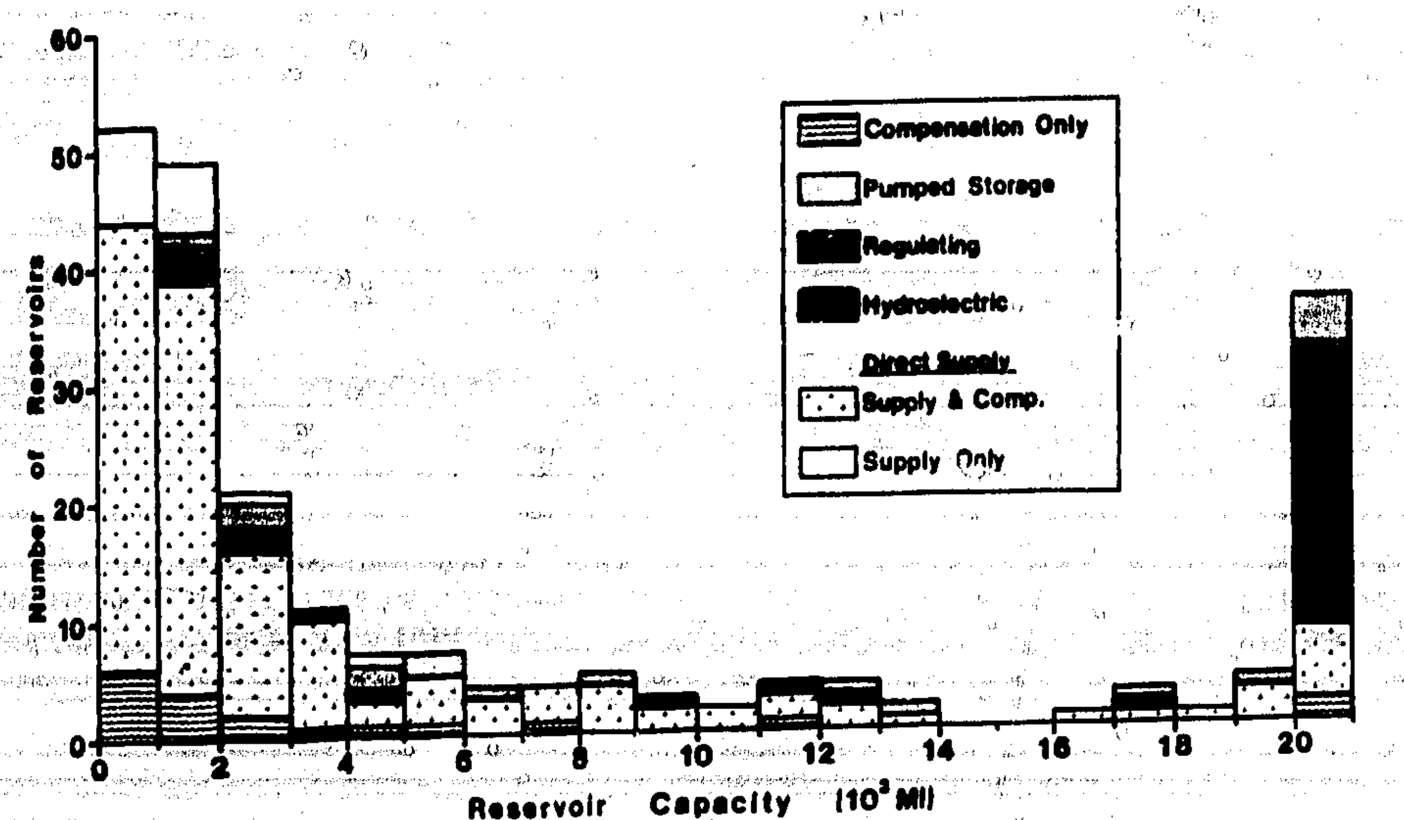


Figure 3.4 Reservoir capacities and variation with reservoir type

'Compensation only' reservoirs, not surprisingly, tend to be of relatively small capacity, though notable exceptions are Loch Venachar (R18004) supplying compensation water for the Loch Katrine group of reservoirs, Bottoms Lodge reservoir (R69029) supplying compensation water for the Longdendale group, and Grimwith reservoir (R27009) in Yorkshire. These all have capacities in excess of 10,000 Ml. (Since these analyses were completed, Grimwith has been operated as a regulating reservoir to support abstractions downstream).

Catchment area

Figure 3.5 shows the distribution of natural catchment areas to impounding reservoirs which follows a pattern similar to that of reservoir capacity. 60% of reservoirs have a natural drainage area of less than 20 km^2, although a further 11% have an area in excess of 100 km^2. The mean catchment area is 54 km^2. Some reservoirs with an extensive catchwater system eg Scammonden, (R27034) have a small natural catchment but large total catchment area.

Net yield

Comparison of yield between reservoirs is difficult, due to the widely differing methods used in its calculation. For some reservoirs the only available estimates of net yield are those calculated at the time of construction, which may have been based on relatively simple rainfall and runoff methods eg Hawksley formula (Ministry of Health advisory committee report, 1930), Lapworth diagram (1949) and Lloyd curve (1953). However, many estimates have since been updated either as a result of a detailed study of water resources using historical or synthetic inflow sequences for individual or groups of reservoirs or by applying regional storage yield relationships to all reservoirs within a Water Authority area eg NWWA (1981). Some of the techniques ascribe a given probability of reservoir failure, whilst others do not. Also a range of different frequencies of failure are adopted. These problems, together with the wide range of reservoir types eg regulating, supply, pumped storage etc. make comparisons of net yield between reservoirs very difficult. Furthermore the widespread development of integrated water resource systems is reducing the value of the concept of a simple yield attached to an individual source.

Despite these shortcomings, the net yield was considered a useful variable in this study in that it enabled the relative size of a reservoir scheme to be appraised and also the division of the gross yield between supply and compensation purposes to be established. Figure 3.6 summarises the distribution of net yield values. 81% of reservoirs have less than 50 Ml/day available for supply purposes; the mean net yield is 65 Ml/day.

3.4 Analysis of compensation flows

3.4.1 Type of compensation release policy

Figure 3.7 shows the type of compensation release policies in use in UK at present and the relative importance of each. There are three main categories of release; namely, a constant discharge, a varying discharge or releases to support a maintained flow at some specified downstream location. Within these broad groupings, there are a large number of minor variations, as detailed on Table 3.4.

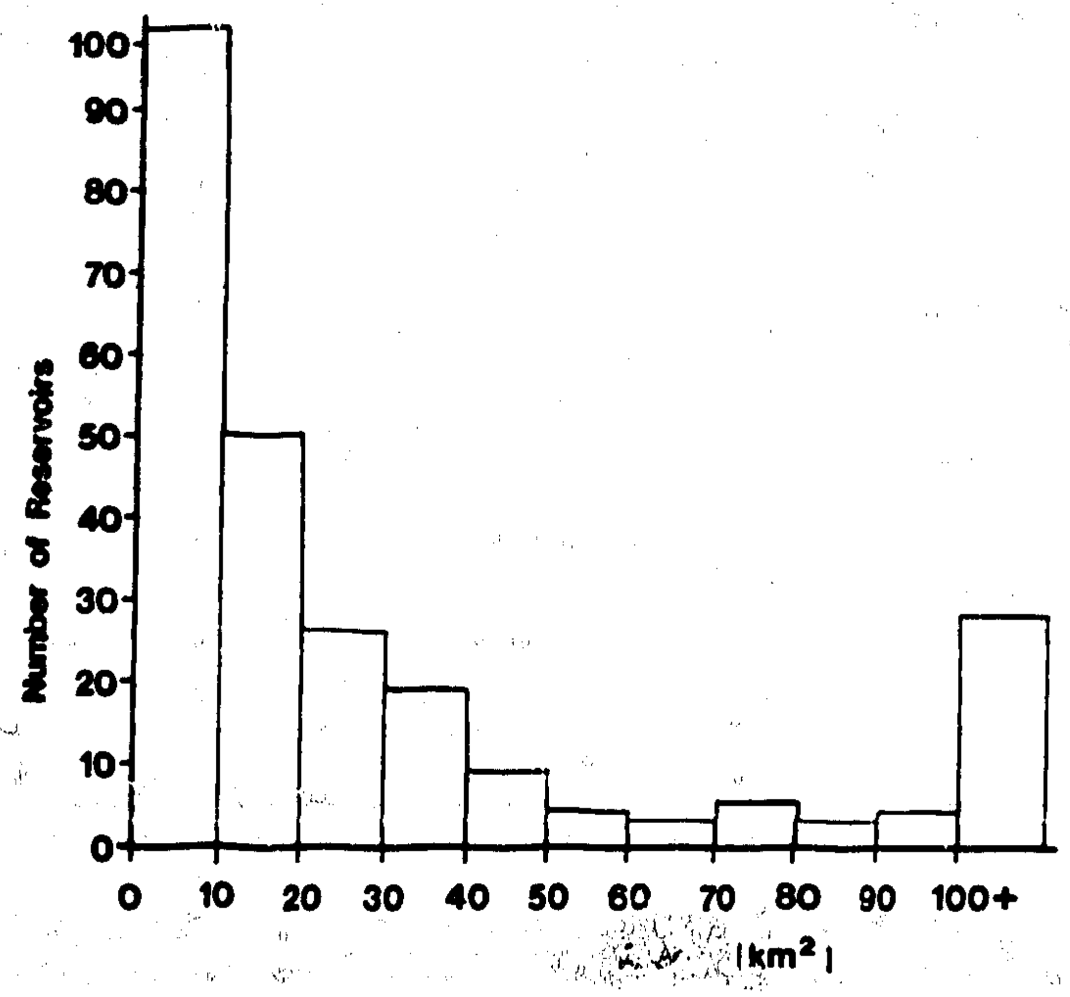


Figure 3.5 Catchment areas of reservoirs

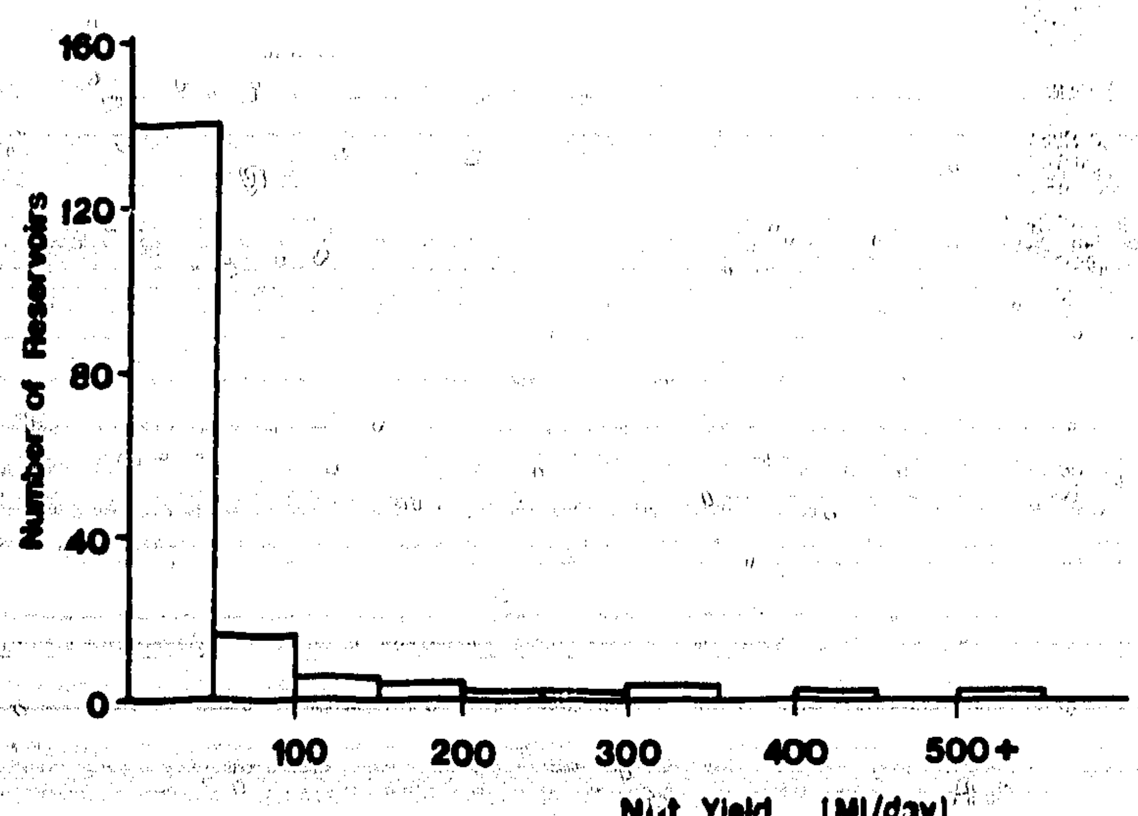


Figure 3.6 Net yields of reservoirs

TABLE 3.4 Methods of releasing compensation water

	Number	
<u>Constant discharge</u>		
Fixed discharge 7 days/week	145	
Fixed discharge 6 days/week (no flow on Sundays)	2	
Constant discharge with freshets and/or block grant	10	
Generally fixed discharge - occasional variations as reservoirs operated together	3	
Constant discharge - divided between several streams	2	
	162	(70%)
<u>Varying discharge</u>		
Seasonally varying flows winter maximum)	1	
summer maximum)	16	
Seasonally varying flows with freshets and/or block grant	13	
Flows varying weekly/daily with control rules	7	
Flows varying within a day	1	
Flows varying with estimated natural flow or flows at an adjacent gauged tributary	1	
	39	(17%)
<u>Maintained flows</u> d/s of dam site		
Constant maintained flow	13	
Seasonally varying maintained flows	2	
Seasonally varying flows and freshets/block grant	5	
Constant flow and freshets/block grant	5	
Varying maintained flow - within a day	1	
" " " - weekly/daily with control rules	2	
Constant flow - made up of releases from several res.	2	
	30	(13%)

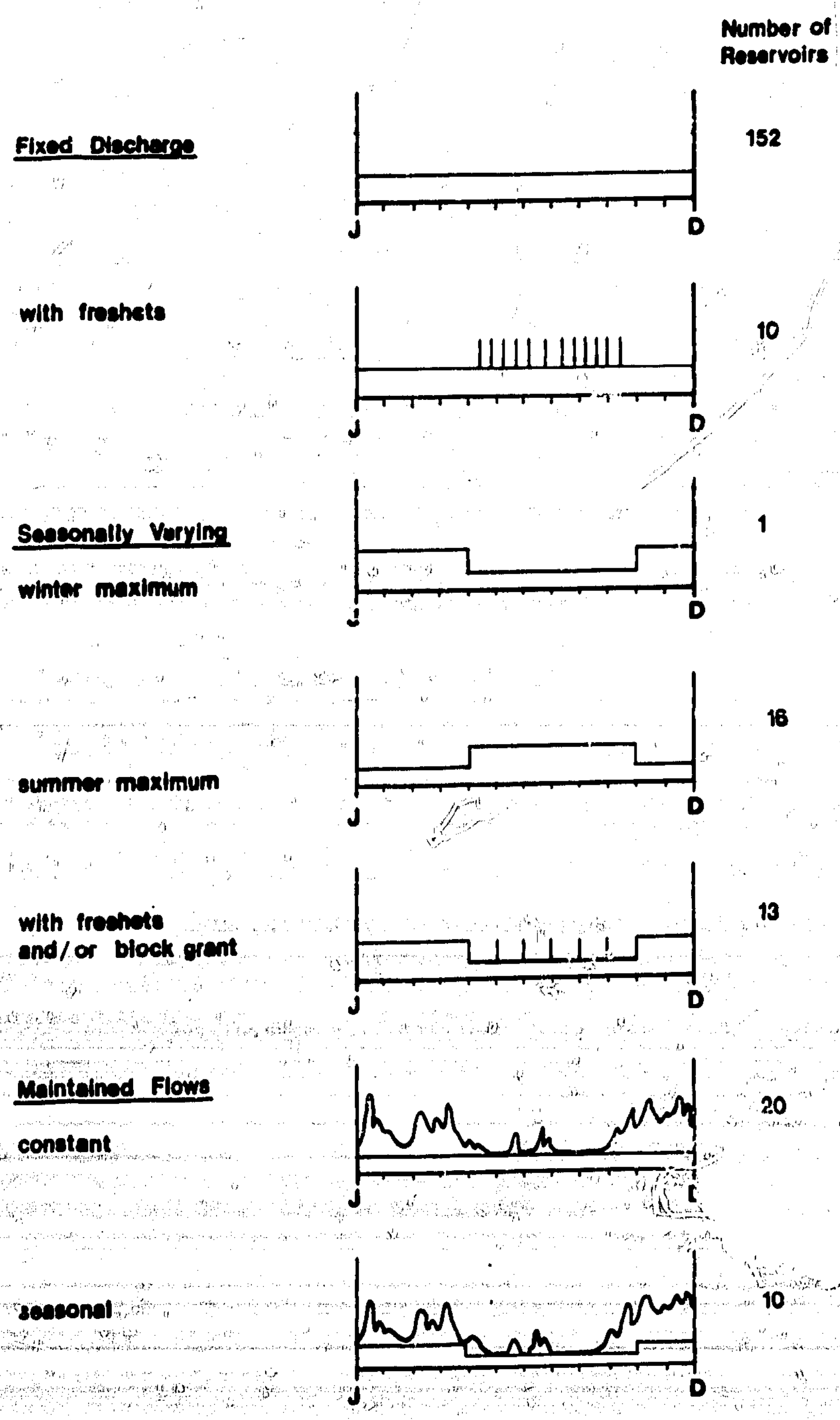


Figure 3.7 Methods of releasing compensation water in the UK

Constant discharge

Over two thirds of reservoirs release compensation water as a single fixed discharge all year (with a few minor variations). Most of these are of the 'dual purpose compensation and supply' or 'compensation only' types. In two instances the constant discharge is maintained for six days per week with zero flow on Sundays - an obvious legacy from the time when industrial interests dominated. A further 10 reservoirs release additional water as freshets or as a block grant during the summer months. Many constant discharge reservoirs are of relatively small capacity, unmanned or on the headwaters of tributaries, so it was often not practical or indeed necessary to devise more complex operating rules.

Varying discharge

Some form of variable release is made at 17% of reservoirs studied, although within this broad category there are many variations. The main types are outlined as follows.

(i) Seasonally varying flows

This is the most common form of variable release occurring at some 30 reservoir sites on the archive. It is often associated with a block grant allowance or with freshets. This more complex type of release policy has generally been introduced on rivers with an important fisheries interest, and as such is particularly prevalent in Scotland (16 reservoir sites). However, South West WA, another region with a strong fisheries interest, has no releases of this type. Values of the ratio minimum/maximum discharge, shown in Figure 3.8, cover the whole spectrum from 0.0 at Talla reservoir (R21001) to 0.91 at Derwent reservoir (R23007), but peak at between 0.2 to 0.3 and at 0.5 to 0.6. This probably reflects the arbitrary use made of 'rule of thumb' estimates, such as a half, or a quarter rather than precise calculations. Figure 3.9 summarises the seasonal range of releases for reservoirs, grouped into areas - most range between 10-30% of the average flow.

With one exception 30 reservoirs release more water in the summer months (normally defined as mid April to September) than winter months (normally October to mid April). This release pattern protects the river against extreme low flows and so was thought to be more beneficial to the river than having the same volume of water released as a constant discharge.

Talybont (R56004) reservoir is the only [illegible] analysed with higher winter releases; from November to Apri[illegible] is released, May to July, 18.2 Ml[illegible] and August to October, 13.6 [illegible], with no allowance for freshets. These flows were set to aid salmon spawning on the Usk tributaries. The only other example known is Elslack reservoir (R27013) in Yorkshire, where the compensation agreement was revised in 1969 to give lower summer than winter releases. This reservoir was of too small a capacity (232 Ml) to be included in the analyses.

Six reservoirs also had flow variations in spring and autumn. Release patterns can occasionally be quite complex. At Gryfe reservoir (R84010) the higher flow is released during the summer from Monday to Friday only, with a return to lower winter flows at weekends. The reasons for this variation were not researched but may be pre[illegible]ed to be associated with a mill located some distance downstream.

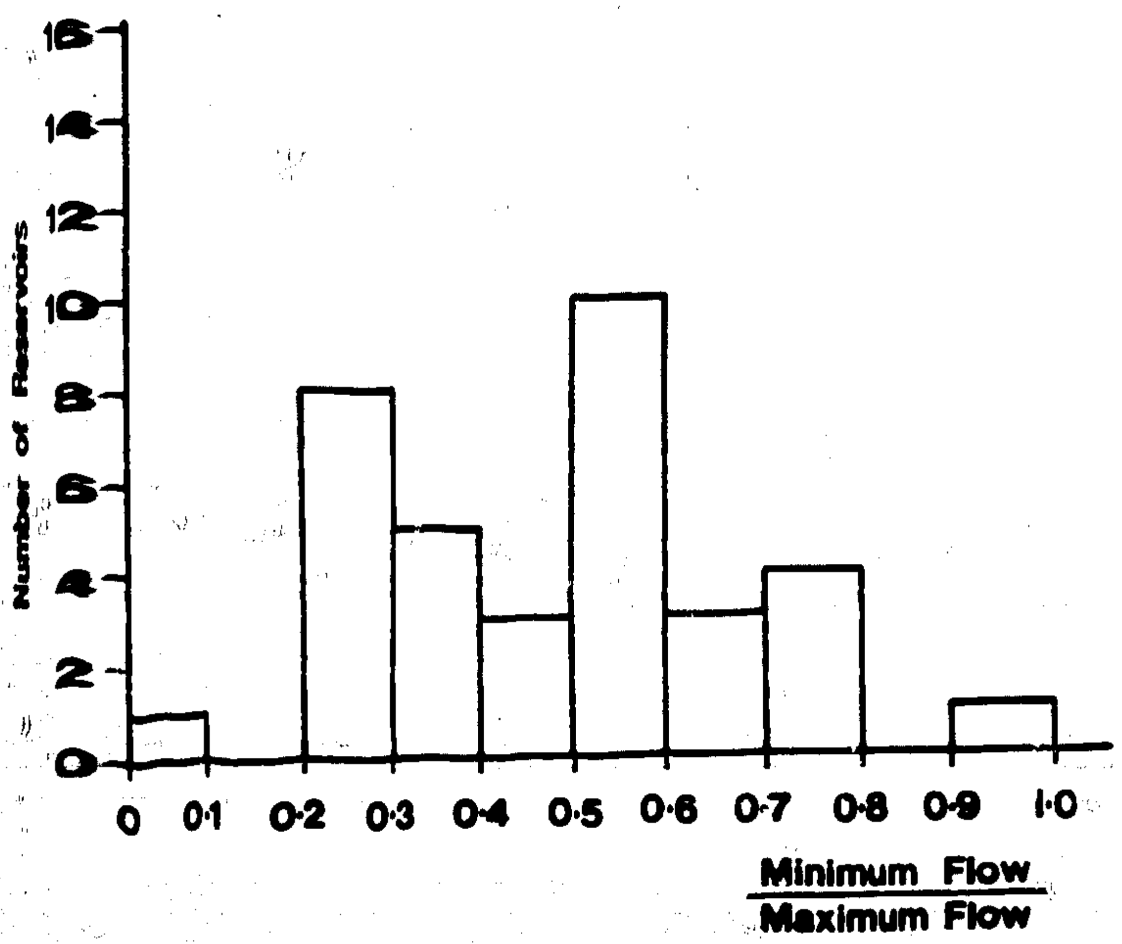


Figure 3.8 Ratio of minimum/maximum flows for seasonally varying releases

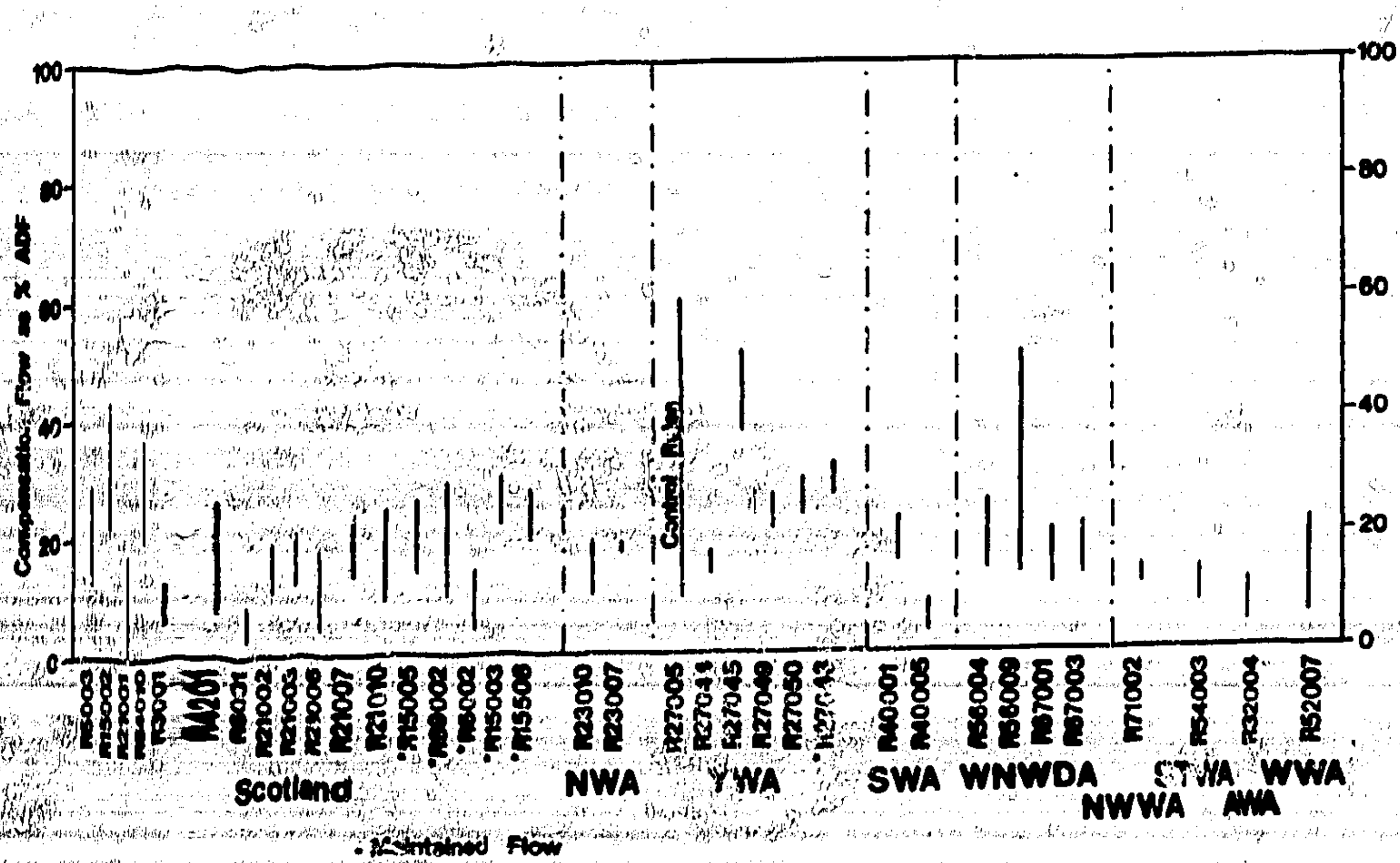


Figure 3.9 Range of seasonally varying releases for different WA areas

(ii) Freshets and block grant

In addition to seasonal variations, water is often released during the summer months as artificial floods or freshets. These are usually designed to aid salmon migration and 'freshen up' the river by flushing stagnant pools. The number of freshets released in a given period is normally specified, as is the maximum discharge and duration of each freshet. There may also be allowance made for block grant releases ie water stored for occasional releases, for instance in a drought or pollution incident. Again, the rate of discharge, maximum flows and total volume of water will be specified.

Nearly half the reservoirs with seasonally varying flows also release water as freshets, normally from mid March to mid October. On important fishing rivers, mainly in Scotland, the freshet release days have to be agreed with the local fisheries board. On R. Tweed, below Fruid reservoir (R21007), freshet releases are made regularly once a week at the same time, regardless of the natural state of the river. In contrast, at Loch Garry (R6002) freshet releases are only allowed when flow in the R. Garry upstream of the loch is naturally high and are therefore used to 'top up' natural spates.

(iii) Others

One of the main other forms of variable release occurs where compensation flows vary with reservoir storage and the time of year. Such control rules have recently been introduced at several reservoirs in Yorkshire WA, as a revision to the traditional constant discharge. At another reservoir, Vyrnwy (R54003) in mid Wales, releases are related to the natural flow regime of an adjacent gauged tributary.

Maintained flows

At 30 reservoirs releases are made to maintain a specified flow at a downstream point rather than at the dam. This maintained flow is often associated with specified minimum releases at the dam, and is common in many Scottish hydroelectric schemes. Maintained flows can be constant, seasonally varying, associated with freshet releases, or daily or weekly variable in the same way as releases at the dam site. About two-thirds of maintained flows on the archive were constant. Those with seasonal variations usually have lower maintained flows in summer than winter eg Deil's Cauldron downstream of L. Lednock (R15005). The flow may also be maintained by releases from several reservoirs, thus increasing the flexibility of the system. Since maintained flows allow for natural runoff between the dam and downstream point, it is increasingly being adopted as a means of conserving supplies and improving flexibility of operation.

3.4.2 Compensation flows

Each compensation flow or maintained flow (COMPFLOW), in Ml/day has been expressed as a percentage of the average natural flow (% ADF) at that point, and is referred to as COMP/ADF. The method for estimating average flows is outlined in Table A3.1. This enables compensation releases from reservoirs of different natural mean discharges to be compared. Where compensation releases are seasonally varying, or where a constant discharge plus freshets are released, it is the discharge which affects the river for the longest period of time which is used in all analyses. Flows varying on an hourly basis have been expressed as an equivalent daily discharge. Compensation flow and average daily flow data of sufficient detail is available for 219 reservoirs (including those with zero releases).

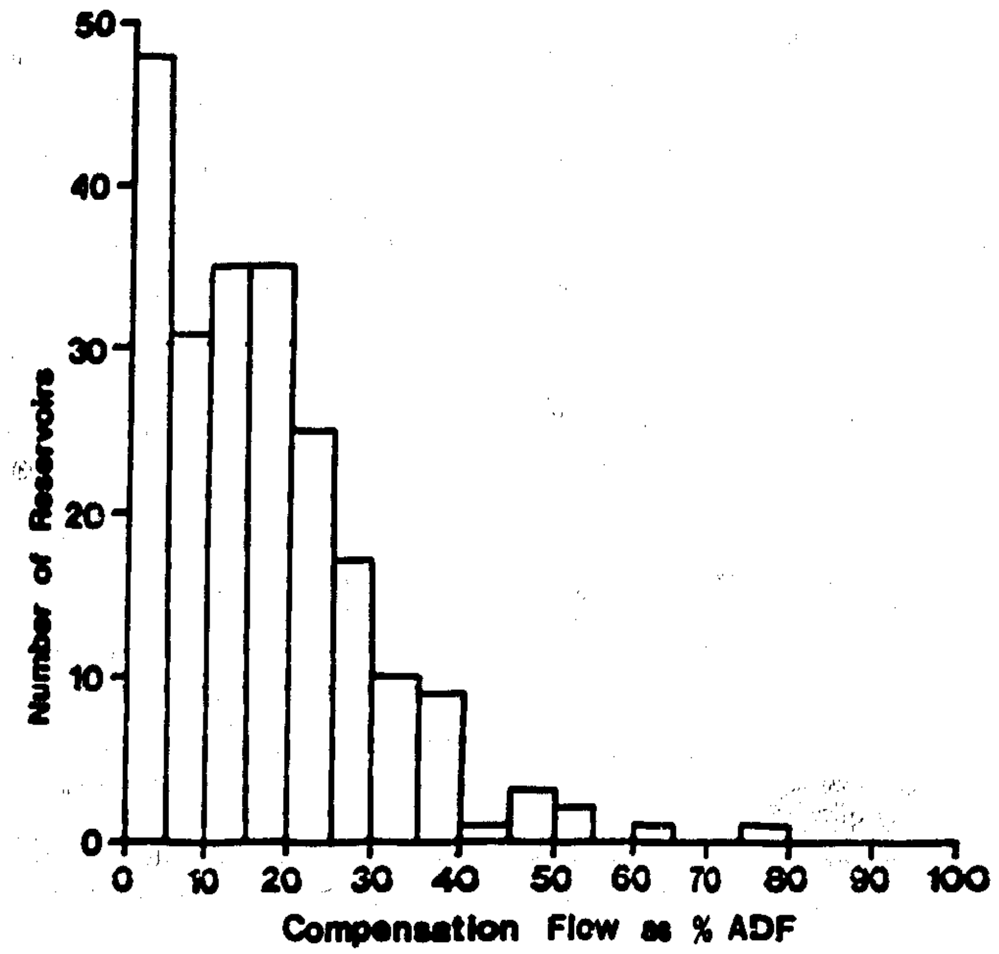


Figure 3.10 Compensation flows, expressed as a % of natural mean daily flow

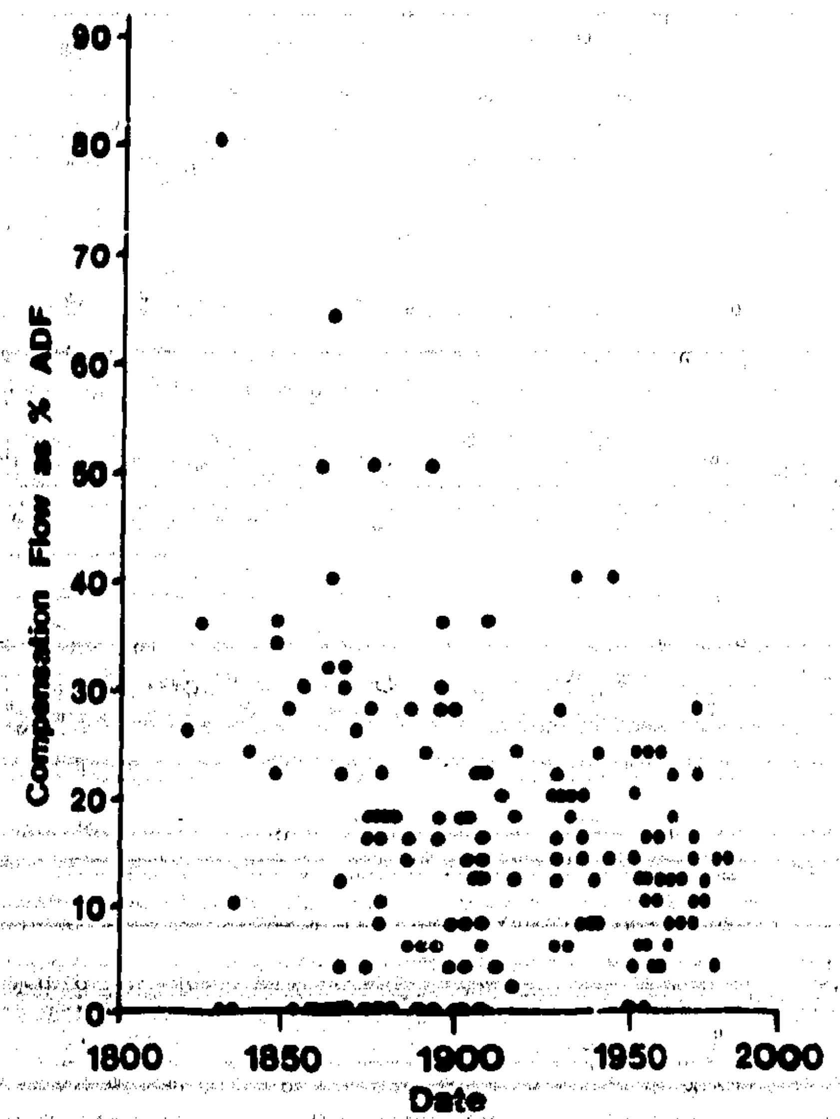


Figure 3.11 Relationship between compensation flows and date of impoundment

TABLE 3.5 MEAN COMPENSATION RELEASES FOR DIFFERENT TYPES OF RESERVOIR

Reservoir Type	Compensation Flow (% ADF)	No.of reservoirs
Compensation only	31.9	18
Supply & compensation	17.3	128
Supply only	0.0	13
Regulating	15.1	18
Pumped storage	9.2	9
Hydroelectric & compensation	15.0	21

Figure 3.10 summarises the distribution of compensation releases. Data for two reservoirs, Scammonden (R27034) and Blackmoorfoot (R27037), have been excluded since the large contribution of runoff from catchwaters makes comparisons of compensation flows with natural flows misleading. Compensation flows at the majority of reservoirs are less than 30% ADF with a peak frequency between 10-15% ADF. The mean compensation value is 15.9% of the natural average flow, although this includes 32 reservoir sites where zero compensation releases are made. The mean compensation release excluding these, is 18.6% of the average flow. The highest award (80% of the average flow) is for Belmont reservoir (R69023), one of the first 'compensation only' reservoirs constructed. Other values in excess of 50% are associated with 'compensation only' reservoirs linked with supply reservoirs (if known) located on a different tributary.

Variations in compensation flow with some of the main reservoir variables were investigated as follows.

Reservoir type

Table 3.5 gives mean compensation flow values for each type of reservoir. The highest mean (31.9% ADF) is associated with 'compensation only' reservoirs, which is to be expected bearing in mind their function. More recent reservoirs, of regulating and pumped storage types, tend to have lower compensation releases, in the range of 9% to 15% of the natural average daily flow.

Date of impoundment

Figure 3.11 examines variations in compensation awards with date of impoundment. Data from all types of reservoir have been included, which may account for the large spread of values. However since only present day compensation releases are recorded on the archive, some of the most extreme original policies will have been reduced. The main trend in Figure 3.11 is toward the elimination of awards in excess of about 30% ADF since 1950. This may reflect the increased use of more objective water resource studies prior to setting compensation flows or the greater priority attached to the supply function of reservoirs in recent times or both. Figure 3.12 shows the reduction in discharge from 'compensation only' reservoirs up until 1920, after which construction of this type of reservoir ceased.

Regional variations

The UK was divided into 12 regions, [illegible]ous with the English and Welsh regional water authorities and with Sc[illegible]land and Northern Ireland each treated as a single entity. It is emphasised that the overwhelming majority of reservoirs were inherited by existing organisations, and that regional differences in awards do not reflect the current policies of these authorities.

The mean compensation release for each region is listed in Table 3.6 and plotted together with the spread of values (mean ± 1 standard deviation) for those regions with a significant number of reservoirs (Figure 3.13). All reservoir types are included. A large variation is apparent with mean compensation flows constituting a higher proportion of the average flow in the Yorkshire (23.9%) and North West areas (19.6%) than elsewhere. When reservoirs making zero compensation releases are excluded mean compensation flows increase to 28.3% ADF in Yorkshire and 23.9% ADF in the North West area. Both these areas are notable for the large number of older and 'compensation only' reservoirs with more generous awards.

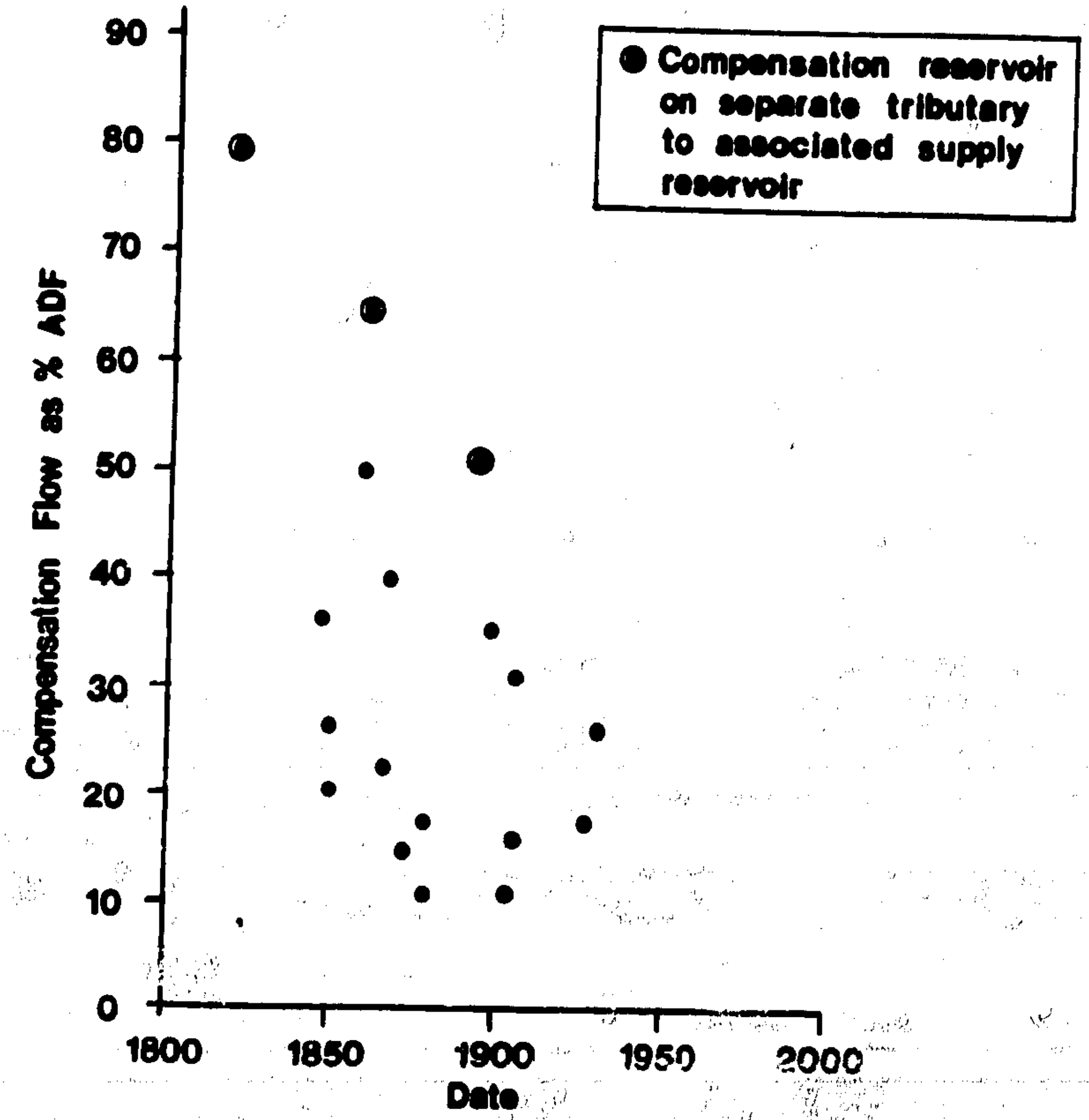


Figure 3.12 Relationship between compensation flows and date of impoundment - compensation only reservoirs

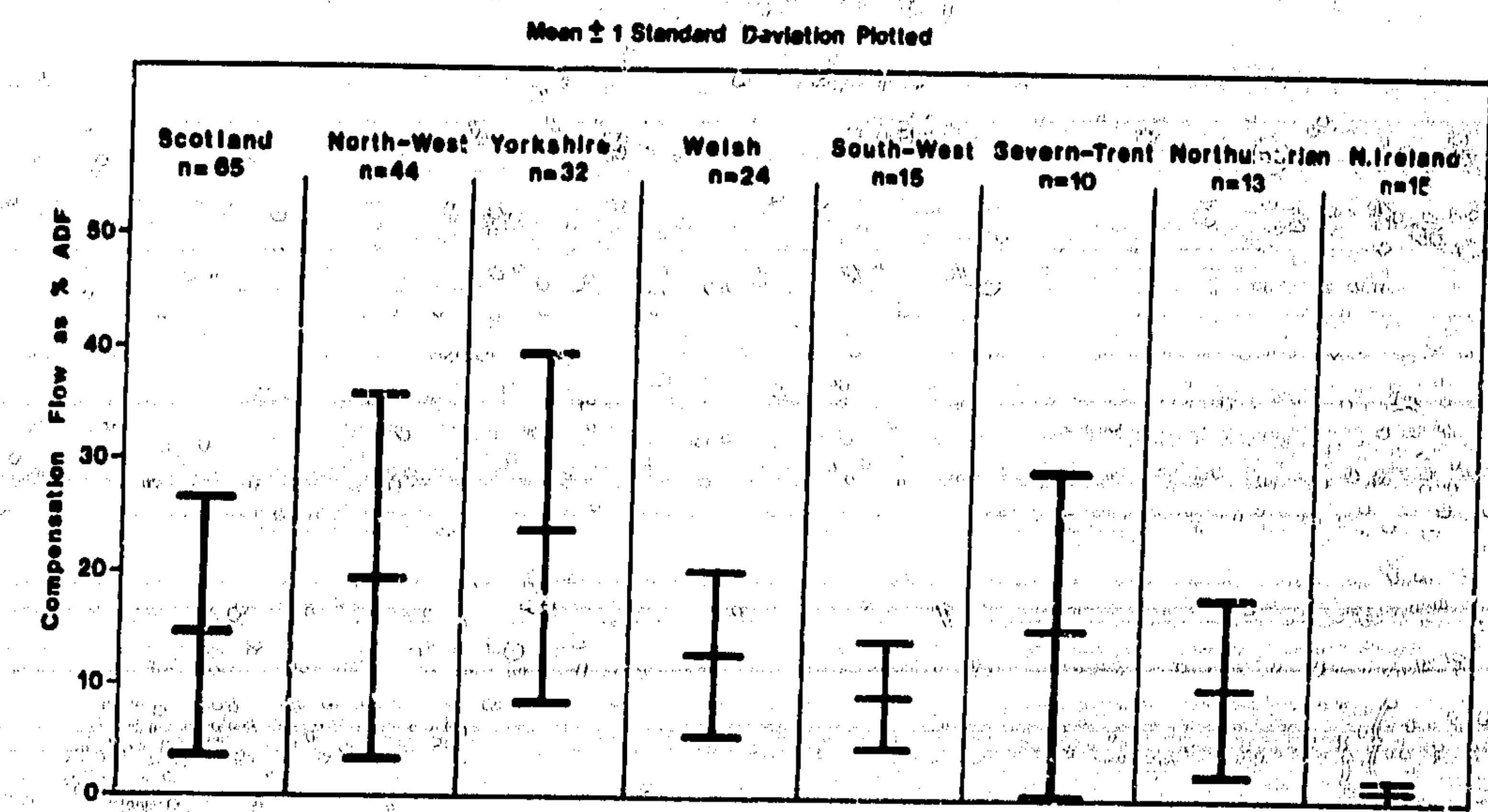


Figure 3.13 Regional variation in compensation flows

TABLE 3.6 **REGIONAL VARIATIONS IN COMPENSATION FLOWS AS A PERCENTAGE OF THE AVERAGE FLOW**

Region	No. reservoirs	Mean compensation flow (% ADF)
Scotland	65	14.6
N. West	44	19.6
Yorkshire	32	23.9
Welsh	24	12.8
S. West	15	9.3
Severn Trent	10	14.5
Northumbrian	13	10.1
Anglian	7	9.6
Wessex	5	10.9
Southern	3	9.7
N. Ireland	15	2.4

Excluding all 'compensation only' reservoirs gives a mean COMP/ADF of approximately 20% ADF for Yorkshire and 18% ADF for North West, which is still higher than Northumbrian, Welsh and Severn Trent WA areas and Scotland which range from 10 to 15% ADF. South West WA and Northern Ireland have low compensation releases of 9.3% and 2.4% of the natural flow respectively (see section 3.5). Most SWWA reservoirs are of a dual purpose or regulating type, while Northern Ireland reservoirs are all direct supply and include nine reservoirs with zero compensation releases.

Gross yield

Figure 3.14 shows the distribution of compensation flows expressed as a percentage of the gross yield for those 152 reservoirs in the subset with available data (excluding pumped storage reservoirs). The distributions for those areas with a significant number of reservoirs with data, namely Scotland, Wales, North West and Yorkshire are also shown.

Despite a wide range of values, the histograms (except for Scotland) show an initial peak with compensation flows up to 10% gross yield, and all exhibit a second peak between 20-40% gross yield (especially marked in Yorkshire). The peak at the low percentage position reflects the large number of instances where a group of reservoirs are operated together for supply purposes, (having a high collective net yield) with only the most downstream reservoir releasing compensation water. In addition 22 reservoirs make zero compensation releases. The second peak almost certainly reflects the prevalence of Hawksley's rule which proposed that compensation flows should be set at a third of the gross reliable yield. It is difficult to establish more specific causal influences, as Hawksley's rule was often the starting point for negotiation, and some compensation flows have in any case been revised since impoundment. Values of compensation flow in excess of 80% of the gross yield (Figure 3.14) relate to the few 'compensation only' reservoirs with associated supply reservoirs located on a different tributary. Other 'compensation only' reservoirs are linked to supply reservoirs on the same tributary so compensation releases can be related to the gross yield of the entire system which is more realistic. The wide distribution of values in Figure 3.14 may also reflect the varied methods and assumptions used to assess net yield in different areas and changes to the yield since reservoir construction.

Compensation flow averaged 25.4% of the gross yield (30% if reservoirs with zero compensation releases are excluded). Three quarters of these reservoirs exceeded 11% and two thirds exceeded 16% of the gross yield. The equivalent figures excluding reservoirs making zero compensation releases are 18.5% and 22% respectively. On an aggregate basis, 22% of the gross yield of reservoirs, in this analysis, is released as compensation water (1626 Ml/day out of 7285 Ml/day).

Downstream Interests

A survey was carried out to investigate the relationship between compensation flows and downstream water quality and fishing interests. The aim was to see if salmon rivers had been awarded higher compensation flows than rivers with no migratory fish. Reservoirs were placed into 3 broad groups according to the dominant downstream interests. The first group covered reservoirs impounding primary salmon rivers. For those rivers in England and Wales the Water Authorities annual reports provided tabulated catch returns for 'game rivers' within their area. Those rivers returning more than 100 salmon in a season were classified as being a primary salmon river. In Scotland rivers with a reputation as fine salmon fisheries were

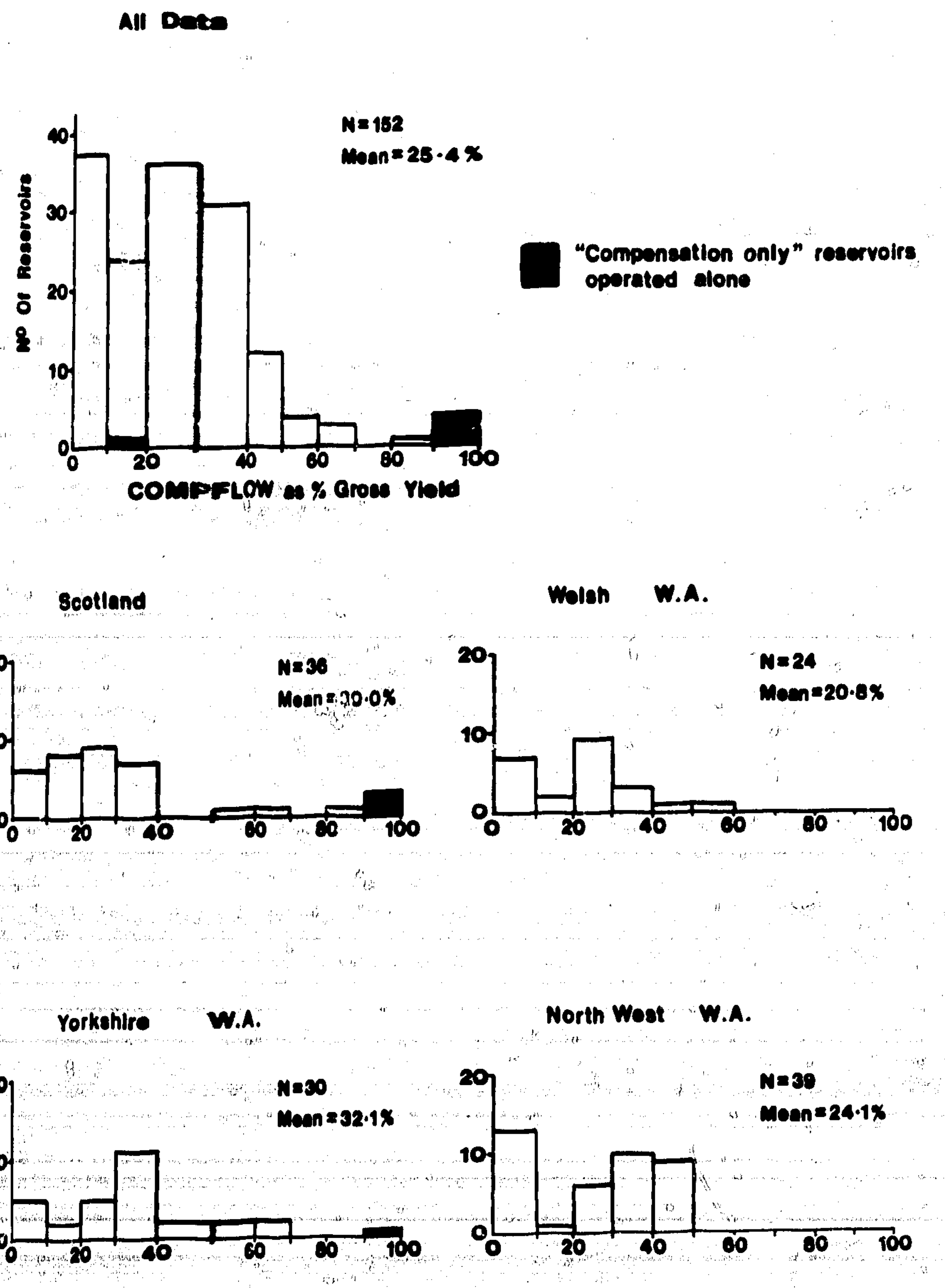


Figure 3.14 Compensation flows as a percentage of gross yield

classified as such and other lesser known rivers likely to hold salmon were also placed in this group. All reservoirs within these river basins, whether they be impounding a small upland tributary or located on the main river, were classified as having important salmon fishing interests downstream.

The second group was made up of reservoirs impounding unpolluted streams, but not primary salmon rivers. The River Pollution Survey of England and Wales was used to establish those rivers which were not important as salmon fisheries but were unpolluted. All reservoirs with at least 10 km of river downstream from the dam designated as chemical class 1 were defined as being unpolluted and placed in this group. Since no pollution survey was available for Scotland the RPBs' annual reports provided a reference for those areas where pollution was thought to be a problem. Reservoirs impounding rivers found to be unpolluted, but without salmon fishing interests, were put in this group.

The third group was made up of reservoirs impounding industrial rivers. The River Pollution Survey of England and Wales was also used to determine those reservoirs with less than 10 km of river designated chemical class 1 below the dam. In Scotland reservoirs on rivers listed in the annual reports as having a long term pollution problem downstream were classified as belonging to group 3.

Overall group 3 reservoirs (industrial) had the highest compensation releases at 20% of the average flow and the largest range of compensation flow releases. Both group 1 (primary salmon rivers) and group 2 (unpolluted) reservoirs had the same mean COMP/ADF of 16% ADF. There is thus no evidence to suggest that salmon rivers have been awarded higher compensation flows than those rivers with no migratory fish. The mean compensation for primary salmon rivers is 2% higher in Scotland than in England and Wales.

3.5 Northern Ireland reservoirs

Table 3.7 lists compensation flow and reservoir data for all reservoirs in Northern Ireland with available data having a capacity in excess of 500 Ml. The Water Services Department of D.O.E. (N.I.) are the operators of all water supply reservoirs and they made available all the data, which have been updated in a study of Water Supply and Demand in Northern Ireland (DOE (NI), 1984). The vast majority of reservoirs in Northern Ireland are of a direct supply type and no regulating or 'compensation only' reservoirs were found. The pumped storage reservoir at Ballinrees was excluded from the analysis due to its small natural catchment.

Over half of reservoirs make no compensation releases at all, and those which do, release water as a simple fixed discharge all year. One exception is Spelga reservoir where the constant discharge is supplemented by four freshet releases a year for fisheries purposes.
Compensation flows are generally low in Northern Ireland, although Camlough, which is a natural lake with the water level raised by impoundment has a compensation discharge of 73% of the natural lake outflow. This is very high and is maintained by a large catchwater area to maintain downstream discharge for a mill. With this 'reservoir' excluded the mean compensation flow in N. Ireland is 2.4% ADF, which includes 9 reservoirs with zero compensation flows. For those reservoirs which make a compensation release the mean value is 6% ADF. Both these figures indicate considerably lower values in Northern Ireland than in the rest of the United Kingdom (see Figure 3.13) and the acceptance of zero compensation flow, particularly from small reservoired catchment areas.

TABLE 3.7 NORTHERN IRELAND RESERVOIRS (IN EXCESS OF 500 Ml CAPACITY)

RESERVOIR NAME	IRISH GRID. REF.	TYPE	TOTAREA km^2	NATAREA km^2	NET YIELD Ml/day	NET CAPACITY Ml	ADF Ml/day	COMPCODE	COMP FLOW Ml/Day	COMP ADF %
Woodburn complex	J378 891	19	28.23	15.64	49.15	8193	33.91	-	0.0	0.0
Silent Valley sys.	J307 218	19	32.40	22.29	107.67	20634	87.45	-	0.0	0.0
Lough Cowey	J593 544	19	4.20	4.20	4.09	804	4.78	-	0.0	0.0
Creightons Green	J430 788	4	1.59	1.59	2.31	545	2.67	0	0.0545	2.04
Stonyford	J215 699	19	13.23	6.83	19.85	3688	12.23	-	0.0	0.0
Killylane	J287 982	19	9.96	2.73	14.64	1327	8.08	-	0.0	0.0
Dungonnell	D193 172	4	11.00	5.10	12.91	945	16.99	0	0.1	0.59
Lough Fea	H764 857	19	10.08	4.00	13.78	1260	10.90	-	0.0	0.0
Altnahinch	D121 235	4	8.83	8.83	11.31	1250	31.40	0	3.21	10.22
Seagahan	H899 381	4	12.35	12.35	15.15	2241	22.35	0	1.14	5.10
Clay Lake	H838 328	4	6.07	5.31	9.20	1882	10.87	0	1.14	10.49
Spelga	J265 272	4	7.04	7.04	19.93	3272	28.72	4	2.27	7.90
Lough Island Reavy	J292 338	19	10.64	1.70	30.10	7683	5.34	-	0.0	0.0
Camlough	J030 259	4	12.12	6.90	9.79	3705	12.58	0	9.09	72.26
Corbet Lough	J178 445	19	3.60	3.60	3.52	727	4.07	-	0.0	0.0
Altnaheglish	J696 041	19	7.28	7.28	15.06	1759	23.10	-	0.0	0.0

3.6 Emergency provisions

The preceding analyses have all been concerned with the statutory obligations of reservoir operators to release compensation water. In certain situations, for instance during an extended period of low flows, it may be difficult or impossible for the operator to fulfill this statutory duty without incurring reservoir failure. In these situations a temporary reduction in compensation releases can be granted by the Department of the Environment, Welsh Office, or Scottish Development Department under a Drought Order. This order states the size of compensation flow reduction and is valid for a specified period only. Secondary applications may be made to extend the period or to override an existing order with more stringent measures. Drought Orders may also be used to limit consumption by banning certain uses of water or for the introduction of standpipes. The method of application and historical background to Drought Orders is outlined in Chapter 2.

There have been several significant droughts in the past two decades and this, coupled with increased demand, has led to a large number of Drought Order applications. These droughts have affected different parts of the United Kingdom to varying degrees. In Scotland and Northern Ireland the 1972/73 drought was generally the most severe, while England and Wales were more affected by the widespread 1975/76 drought. In contrast the 1984 drought was of a shorter duration and less widespread in its effects, although in parts of western Britain it was of comparable or greater severity.

The size of flow reductions and the frequency with which Drought Orders are required are an important part of compensation flow policy. In 1984 a large number of restrictions on consumption and reservoir releases were necessary to maintain supplies. In the following section the response to the 1984 drought in England and Wales, in terms of reductions to compensation flows is examined. Suggested legislative changes arising from operational experiences in the 1984 drought are noted in Chapter 2.

3.6.1 1984 Drought

As Table 3.8 shows, a total of 115 Drought Orders were made in England and Wales during the summer of 1984. Worst affected regions were the South West (44 Drought Orders), North West (31 Orders) and Wales (25 Orders). No other Water Authority apart from those shown in Table 3.8 found it necessary to restrict compensation releases. The figure of 7 Drought Orders only for Yorkshire is misleading as 2 Orders allowed for reductions in compensation flow of either 1/3 or 2/3 depending on the aggregate storage, at a total of 42 reservoir sites. This type of regional Drought Order certainly reduces administrative time, where there are a large number of small reservoirs in an area. It is notable however that Orders were not required at any of the five Yorkshire reservoirs where control rules had been introduced (Section 3.4.1).

Approximately half of the Orders enabled a reduction in compensation releases; or occasionally a change in releases to support abstractions downstream. A further 29% of Orders were connected with abstractions, while 14% enabled consumption to be restricted, particularly in Wales and South West. Table 3.9 lists the reductions in compensation flows made during the 1984 drought, which are summarised in Table 3.10. The average reduction in compensation flows is to 46% of the original compensation flow, though the range is wide from 6-87%. At 4 reservoirs in NWWA, and 6 reservoirs in SWWA, it was necessary to override an existing Drought Order by a second, more stringent Order, and in general these further reduced compensation flows to 16% of the statutory compensation release. Formal objections were raised to only 7 of the 55 applications for Drought Orders, most coming from fisheries and angling interests.

3.7 Conclusions

The main findings of this survey of compensation flows may be summarised as follows:

1. Information on compensation flows and other reservoir details was not readily available from one source and tended to be piecemeal and of varying reliability.

2. Three main methods of releasing compensation water were used. About 70% of reservoirs released a simple fixed discharge. 17% of reservoirs had some form of variable release (normally seasonally varying flows with a summer maximum), occasionally supplemented by the release of artificial floods or freshets and/or a block grant allowance for contingency purposes. 13% of reservoirs maintained a specified flow (constant or variable) at a downstream point rather than at the dam.

3. The size of compensation releases as a percentage of the natural flow varied considerably between reservoirs. Most released less than 30% of the natural average flow with a mean of 18.6% (excluding reservoirs making zero compensation releases). The highest releases were from 'compensation only' reservoirs.

4. There had been a trend in recent years towards a more consistent approach to setting compensation flows and since 1950 there had been no extreme awards, in excess of 30% of the natural flow.

5. There were large regional differences in the level of releases. Those reservoirs now in Yorkshire and North West WA's had the highest releases of 24% and 20% of the natural average flow respectively. This reflected the historical influence of millowners in 19th century. In contrast, releases in SWWA and N. Ireland were very low at 9.3% and 2.4% of the average flow respectively. Over a half N. Ireland reservoirs made no compensation release at all.

6. No evidence was found that higher releases had been made on salmon rivers than those with no migratory fish. The highest releases were on industrial rivers.

7. Compensation releases as a percentage of the gross yield varied considerably although a peak in the distribution between 20-40% of the gross yield was evident. This reflected the frequent adoption, particularly in the Pennine area, of Hawksley's suggestion that a third of the reliable yield be reserved for compensation purposes. However, the wide scatter of awards suggested that this was perhaps the starting point for negotiation and not the final figure.

8. On an aggregate basis 22% of the total gross yield of reservoirs studied was released as compensation water.

9. During the 1984 drought, Drought Orders were widely used as a means of restricting compensation releases. Compensation flows were on average reduced to 46% of the original, although the range was wide from 6-87%. At 10 reservoirs it was necessary to override an existing Drought Order by a second more stringent Order, reducing flows to an average of 16% of the normal statutory compensation flow. Formal objections were raised to only 7 out of 55 applications for Drought Orders.

TABLE 3.8 REGIONAL SUMMARY OF DROUGHT ORDERS MADE DURING 1984 DROUGHT

Type of order	Number of orders/region						
	NWWA	SWWA	STWA	YWA	WNWDA	WATER CO	TOTAL
(a) Reduction in compensation flows and reservoir releases	21	15	3	3	12	1	55
(b) restrictions on abstractions	7	14	2	2	7	1	33
(c) restrictions on use and supply	1	7	1	2	5	-	16
(d) other	2	8	-	-	1	-	11
(e) total	31	44	6	7	25	2	115

TABLE 3.9 SUMMARY OF REDUCTIONS IN COMPENSATION FLOWS

	NWWA	SWWA	STWA	YWA	WNWDA	WATER CO	MEAN
Primary reduction: Mean revised compensation flow as % statutory compensation flow	46	47	44	*	31	60	46
Secondary reduction: Mean revised compensation flow as % statutory compensation flow (where applied)	19	16	-		12	60	16
No of Orders made	21	15	3	3	12	1	
No of objections raised	3	2	0	0	2	0	

* Size of reduction varies with reservoir storage

TABLE 3.10 REDUCTIONS IN COMPENSATION FLOW MADE IN 1984 DROUGHT ROUGHT ORDER

RESERVOIR	DATE ORDER MADE	STATUTORY COMP. FLOW (Ml/day)	NEW COMP. FLOW (Ml/day)	NEW FLOW AS % STATUTORY FLOW
North West Water Authority				
Ashworth Moor	19/6/84	4.55	0.454	10.0
Cowpe	19/6/84	0.875	0.454	52.0
Clowbridge	19/6/84	3.669	2.00	54.5
	31/7/84		1.00	14.8
Delph	19/6/84	2.15	0.682	31.7
	12/9/84		0.455	21.1
Jumbles	19/6/84	13.8	9.79	70.9
	12/9/94		4.99	36.2
Wayoh	19/6/84	2.447	0.563	23.0
Haweswater & Wet Sleddale	12/7/84	29.23 (combined releases)	16.55	56.6
Stocks	23/7/84	18.184 (May-Sept release)	9.092	50.0
Hurst	25/7/84	1.136	0.454	40.0
Swineshaw	25/7/84	0.856	0.227	26.6
Lamaload	27/7/84	1.818 (max. release)	1.136	62.5
Bottoms + Teggsnose	31/10/84	2.387	1.137	47.6
Rivington	[illegible]/8/84	4.681 3.915 4.894 (3 releases to river, works & mill)	6.652 3.426 2.936	46.7 87.5 60.0
Blackmoss	5/9/84	[illegible].555	1.200	33.7
Lower Coldwell	5/9/84	0.909	0.227	25.0
Greenbooth	14/9/84	6.364	1.818	28.6
Thirlmere	7/9/94	13.638	9.092	66.6
South West Water Authority				
Stithians	21/6/84	2.7	1.35	50.0
	27/7/84		0.16	6.0
Meldon	19/7/84 6/[illegible]/84	7.73	Suspended except to augment Torridge	
U. Tamar Lake	4/7/84	2.7	1.35	50.0
			0.68	25.2
Burrator	6/8/84	2.618	1.14	43.5
Fernworthy	3/8/84	5.68	3.41	60.0
	13/8/84		1.364	24.0
Avon	27/7/84	5.91	2.27	38.4
	8/8/84		0.455	7.7
Venford	20/7/84	1.82	0.68	37.4
Drift	23/7/84	1.36	0.68	50.0
	7/9/84		0.227	16.7

TABLE 3.[illegible] REDUCTIONS IN COMPENSATION FLOW MADE IN 1984 DROUGHT BY DROUGHT ORDER

RESERVOIR	DATE ORDER MADE	STATUTORY COMP. FLOW (Ml/day)	NEW COMP. FLOW (Ml/day)	NEW FLOW AS % STATUTORY FLOW
Welsh Water Authority				
Taf Fawr	20/6/84	19.093	9.547	50.0
	27/7/84		2.273	11.9
[illegible]ynnon Llugwy	3/9/84	4.[illegible]	2.273	50.5
Llyn Cwellyn	16/7/84		6.819	
Cwmystradllyn	3/7/84	[illegible].91	Suspended	
Llyn Eiddew	20/7/84	0.227	Suspended	
Cray	3/[illegible]/84	6.819	2.273	33.3
Prescelly	25/7/84	1.818	0.227	12.5
Elan Valley	23/8/84	118.[illegible]9	45.459	38.5
Talybont	23/8/84	13.6 (Aug-Oct)	2.727	20.0
		25.0 (Nov-April)		(10.9)
Severn Trent Water Authority				
Ladybower	14/8/84	75.762	39.393	52.0
		17.047 (R. Derwent + Jaggers Clough respectively)	6.064	35.5
Clywedog	17/8/84		Suspended, but subject to conditions-rate of flow at Bewdley, reservoir storage etc.	

RESERVOIR	DATE ORDER MADE	STATUTORY COMP. FLOW (Ml/day)	NEW COMP. FLOW (Ml/day)	NEW FLOW AS % STATUTORY FLOW
South Staffordshire Water Company				
Blithfield	29/8/84	22.73	13.64	60.0
Yorkshire Water Authority				
[illegible]	23/8/84	13.661	13.661 (when storage > 3182 Ml)	
			9.107 (when storage 1591-3182 Ml)	66.6
			4.554 (when storage < 1591 Ml)	33.3
Scargill, Beaver Dyke, Ten Acres	23/8/84	0.909	0.605 (when storage in 3 reservoirs 505-1009 Ml)	66.6
			0.305 (when storage < 505 Ml)	33.5
Bradford & Craven reservoirs (9 reservoirs)	19/9/84	Compensation at each reservoir reduced by 2/3, when total amount of storage in 9 reservoirs is < 1924 Ml; reduced by 1/3 if storage 1924-2565 Ml.		
Pennine reservoirs (33 reservoirs)	27/7/84	Compensation at each reservoir reduced by 2/3, when total amount of storage in 33 reservoirs < 22,860 Ml; reduced by 1/3 when storage 22,[illegible]00-30,530 Ml.		

4. CHANGES IN FLOW REGIME FOLLOWING RESERVOIR IMPOUNDMENT

4.1 Introduction

The change in flow regime following impoundment can be estimated by comparing flow records before and after impoundment or by comparing naturalised inflow records with gauged outflows. The former method has the disadvantage that comparisons are complicated by differences in the natural flow regime over the two periods. Although comparisons of gauged and naturalised flows are not affected by such changes, large errors are associated with estimation of natural inflows from the rate of supply, compensation, spill and change in reservoir storage. In order to study the change in flow regime below as many reservoirs as possible, both approaches have been used in this study. In comparing pre and post impoundment records it was important that the gauging station used was not too far downstream from the reservoir, that a minimum of 5 years of before and after data were available and that the pre impoundment record was indeed 'natural' and not also influenced by artificial controls. As a result of these constraints only 3 suitable pre and post impoundment records were available. The remaining comparisons were based on naturalised reservoir inflows and gauged outflows. Table 4.1 lists the reservoirs and flow records used in the comparison and their locations are shown on Figure 4.1. Although comparisons of data are useful for summarising the observed changes to flow regimes, for a specific reservoir scheme a reservoir simulation should be carried out to determine the effect of different operating policies on downstream flows.

4.2 Change in flow regime

Figure 4.2 shows the change in discharge regime following impoundment approximately 5 km downstream of Blithfield Reservoir located in the Severn Trent Water Authority area. The changes are typical of those below many reservoirs with the low flow regime being determined by the statutory compensation discharge and flood flows being dependent on the reservoir inflows, releases, volume of storage and spillway characteristics. Reservoirs supplying high yields with respect to their mean annual inflow produce a greater reduction in the frequency of flood discharge than reservoirs with smaller yields. This is because the latter are full for much of the winter period and hence have less capacity to attenuate flood inflow.

For the 29 sites located below impounding reservoirs used in the analysis (Figure 4.1), the mean annual runoff was reduced on average to 55% of the pre impoundment value with a maximum reduction to 12% of the natural mean discharge. Daily and monthly flow duration curves have been used to summarize the changes in frequency of discharges standardised by the pre impoundment natural mean discharge. As a typical example, Figure 4.3 shows a change in the daily flow duration curve following impoundment of the R. Blithe. It can be seen that although there has been a reduction in discharge throughout the flow range, the reduction in low flows is very small with the pre and post impoundment 95 percentile discharge (Q95) showing little change. Figure 4.4 shows the change in monthly flow duration curve below Scout Dike reservoir, within the Yorkshire Water Authority area, where the low flows have been increased following impoundment. The 95 percentile discharge in this example has increased from a pre impoundment value of 6% of the natural mean discharge to 21% of the natural mean discharge. Pairs of flow duration curves were

TABLE 4.1 **RESERVOIRS AND GAUGING STATIONS USED IN CHANGE IN FLOW REGIME STUDY.**

RESERVOIR	RESERVOIR TYPE*	GAUGING STATION	PERIOD OF RECORD
Tummel	Hydroelectric, comp releases	15012	1/75- 9/80
Rosebery	Compensation only	19008	10/65-12/75
Cobbinshaw	Hydroelectric, comp releases	19009	1/63-12/76
Derwent	Supply and compensation	23002	1/55-12/64 (Pre reservoir) 10/65- 9/71 (Post reservoir)
Gouthwaite	Compensation only	27005	10/36- 6/76
More Hall	Compensation only	27013	10/54- 9/71
Underbank	Compensation only	27016	10/56- 6/76
Scout Dike	Compensation only	27020	10/56- 9/73
Lindleywood	Compensation only	27911	10/53- 9/73
Widdop Group	Supply and compensation	27912	10/54- 9/71
Ryburn	Supply and compensation	27918	10/56- 9/73
Digley	Supply and compensation	27939	10/67- 9/71
Ladybower	Regulating	28001	1/66-12/77
Blithfield	Supply and compensation	28002	1/38-12/52 (Pre reservoir) 1/54-12/80 (Post reservoir)
Eyebrook	Supply and compensation	31001	10/65- 9/71
Weirwood	Supply and compensation	40001	10/53- 9/67
Darwell	Pumped storage	40002	1/63- 9/75
Sutton Bingham	Supply and compensation	52902	10/56- 8/68
Clatworthy	Supply and compensation	52908	10/60- 8/68
Chew Valley Lake	Supply and compensation	53004	1/59-12/76
Vyrnwy	Regulating	54003	1/31-12/77
Caban Coch	Supply and compensation	55006	10/35- 6/77
Taf Fechan	Supply and compensation	57001	10/52- 9/67
Brenig	Regulating	67003	3/22-12/74 (Pre reservoir) 1/77-12/81 (Post reservoir)
Bottoms	Compensation only	69004	1/45- 9/68
Stocks	Supply and compensation	71002	1/62-12/81
Thirlmere	Supply and compensation	75001	10/35- 5/76
Haweswater	Supply and compensation	76001	10/53- 9/70
Penwhirn	Supply and compensation	81003	1/68-12/71

* Dual purpose reservoirs classified by dominant influence on downstream river flows.

Figure 4.1 Location of reservoirs

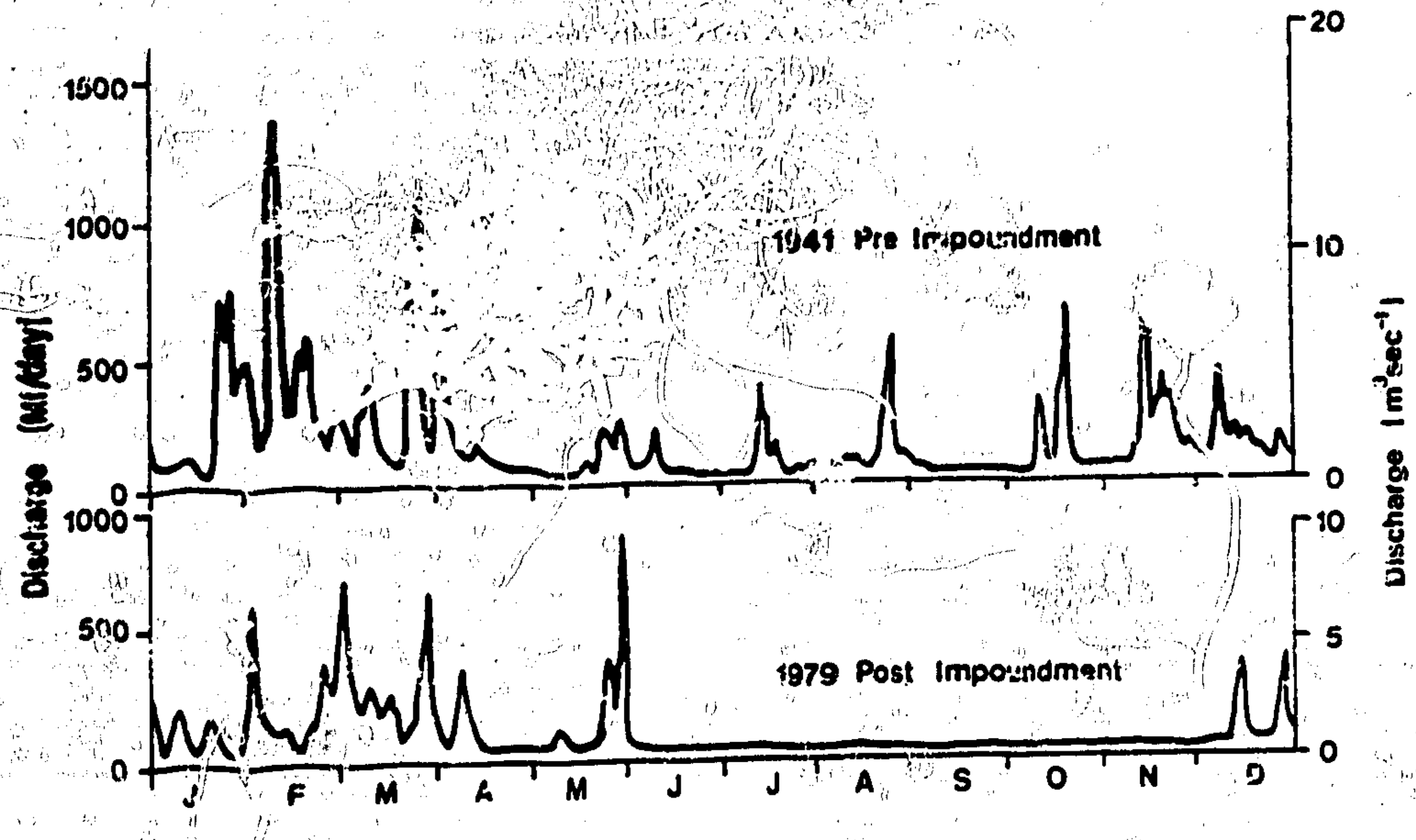


Figure 4.2 Typical pre and post impoundment flow regime on the River Blithe

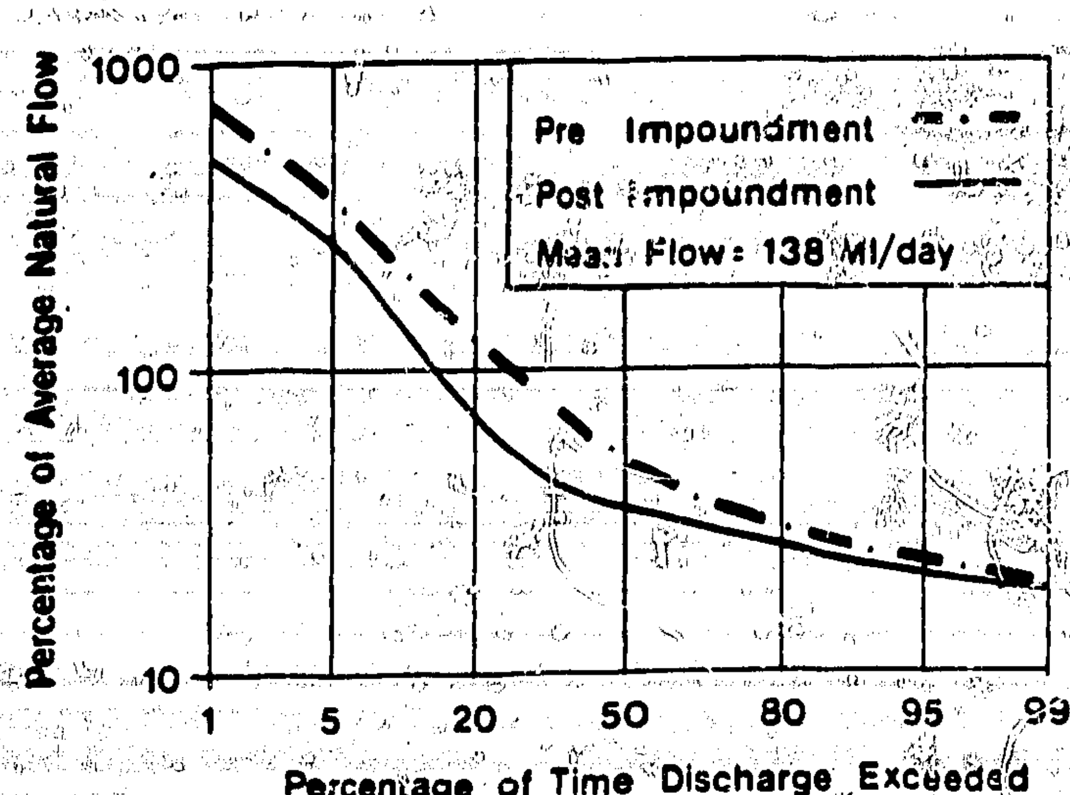


Figure 4.3 Pre and post impoundment flow duration curves below Blithfield reservoir

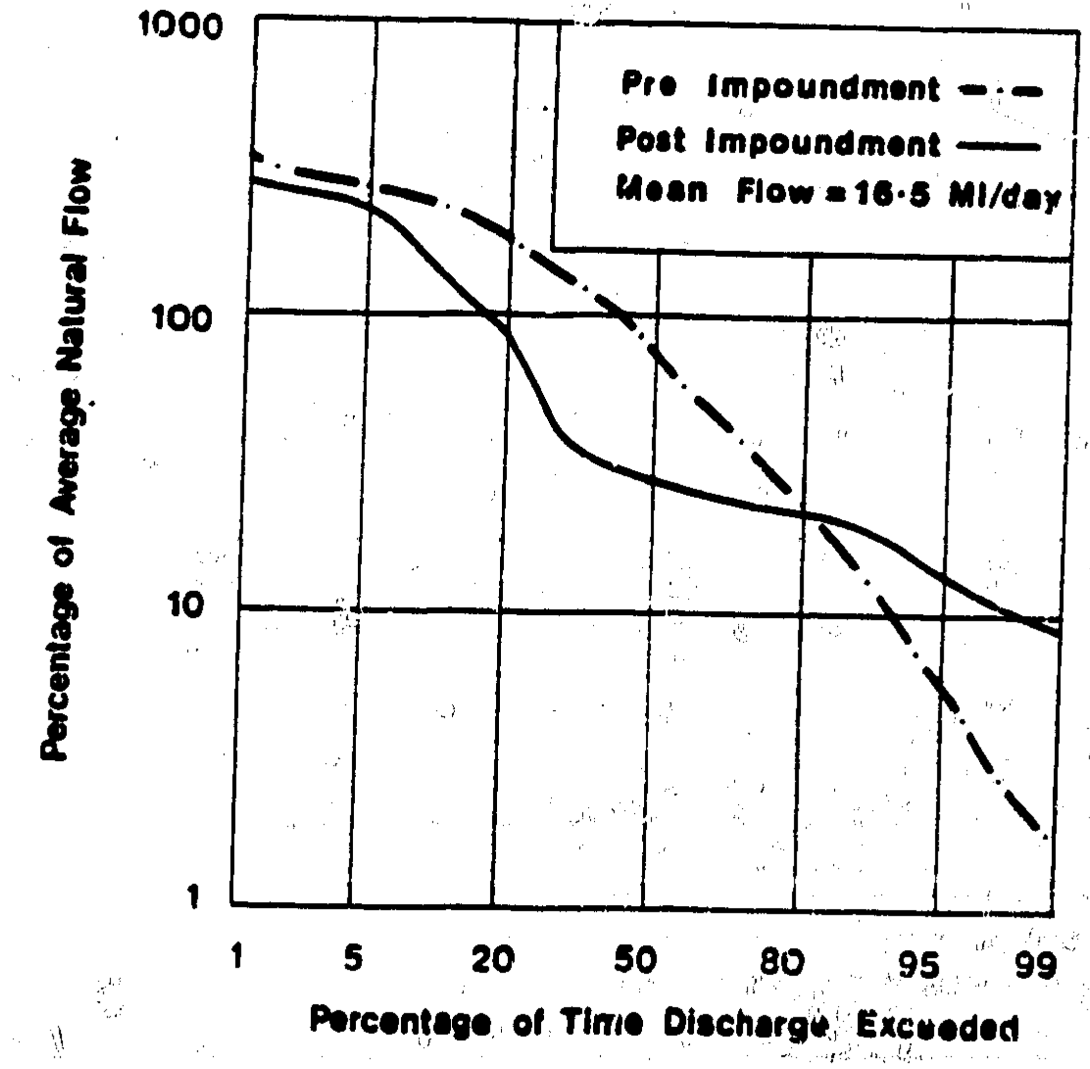


Figure 4.4 Pre and post impoundment flow duration curves below Scout Dike reservoir

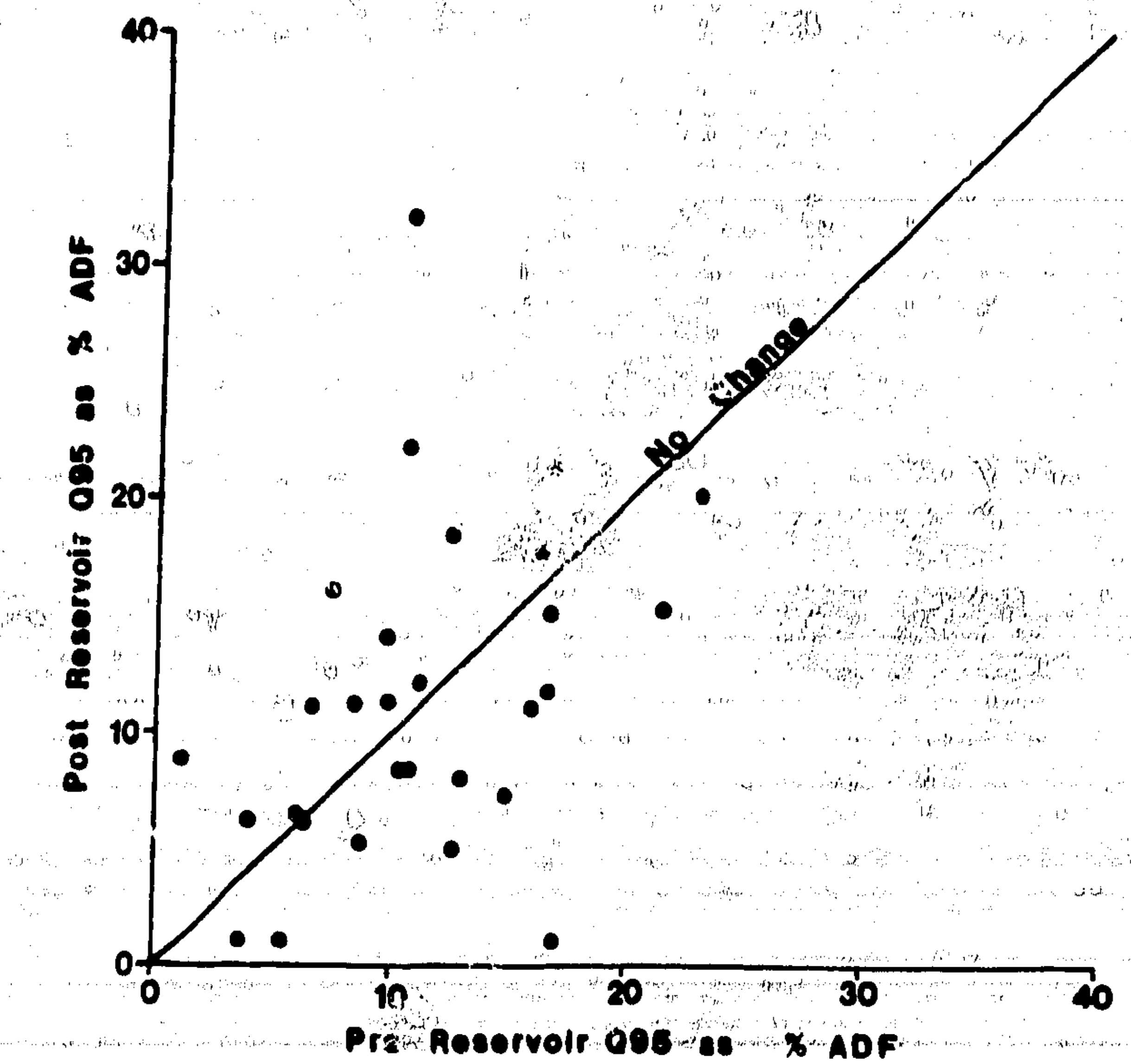


Figure 4.5 Change in 95 percentile discharge following impoundment

calculated for each of the 29 sites and the changes in flow regime have been investigated by comparing the pre and post impoundment flow for different exceedance frequencies. Figure 4.5 shows the 95 percentile discharge before and after reservoir impoundment. All percentiles are based on 1 day flow duration curves and where necessary have been converted from monthly to a daily base using methods described in the Low Flow Studies Report (Institute of Hydrology, 1980). Although the average 95 percentile discharge over all 29 schemes shows no significant change between pre (11.2% ADF) and post impoundment (11.5% ADF) conditions, wide departures from maintaining the natural low flows exist. The figure also illustrates the wide range of natural low flow behaviour from one reservoir site to another. The lowest and highest observed values of Q95 were respectively 1% and 23% of the natural mean discharge.

If a policy is adopted of ensuring that compensation flows are set no lower than the natural low flow regime, then this variability must be taken into account. This precludes the use of a fixed percentage of the average natural flow being used as a 'standard' compensation flow. Such a policy would result in the chosen compensation flow being a relatively common discharge on some catchments, whilst on others it would be substantially below the minimum historic flow.

Figure 4.6 shows the change in the 80 percentile flow following impoundment. It can be seen that, for the majority of reservoirs, the discharge for this exceedance frequency has been reduced following impoundment, although five sites with generous compensation discharges exhibit higher post reservoir flows. Comparisons of the complete flow duration curves for all sites indicated that the greatest reduction in discharge was between the 10 and 90 percentile flow with, for example, an average reduction of the median flow, Q50, to 43% of the pre impoundment value.

4.3 Changes in flood characteristics

4.3.1 Mean annual flood

The change in the downstream flood regime following impoundment has rarely been estimated at the design stage and with one or two exceptions the environmental consequences of any changes have received little attention. Where the flood flows have been considered important, notably in rivers with migratory fishing interests, artificial freshets or flood releases have been used in an attempt to reduce the ecological damage caused by prolonged low flows. Figure 4.7 shows the relationship between the calendar day mean annual flood before and after impoundment. The calendar day mean annual flood prior to regulation has been estimated from the characteristics of the drainage basin (NERC 1975) and compared to gauged post impoundment values. Reductions to 5% of the natural flood discharge occur below some reservoirs with an average reduction to 74% of the natural value. These changes exist close to the dam and will gradually reduce as one moves further downstream.

4.3.2 Changes in frequency of spates

Of more interest for fisheries management purposes, particularly for rivers with important migratory fish populations, is the change in frequency of flood flows. To assess the effect of impoundment on the number of spates which would occur on a natural river a comparison of gauged and naturalised daily flows below reservoirs was made. Two sets of hydrographs were produced for those gauging stations sited below eight reservoirs with gauged and naturalised flow data for the same period of

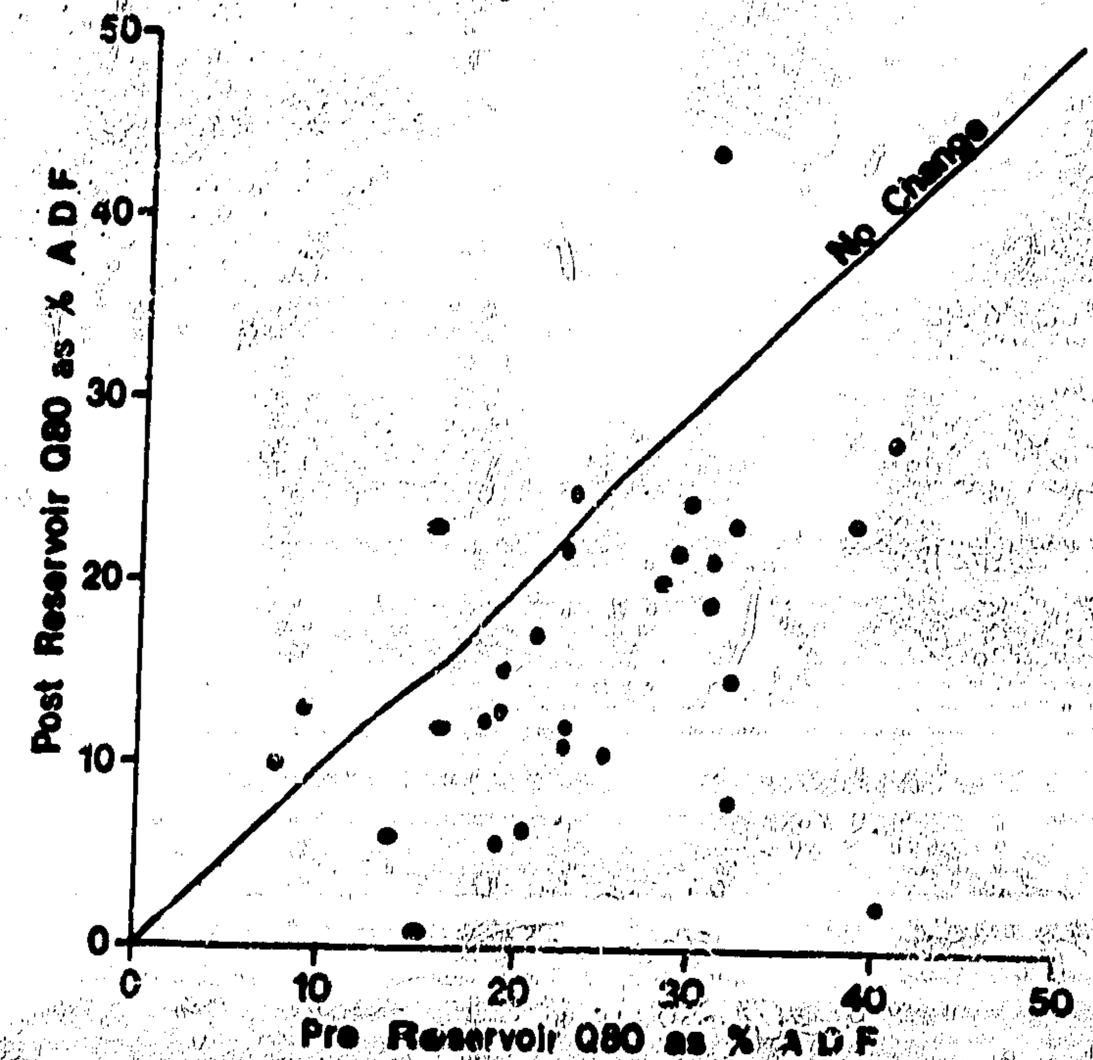


Figure 4.6 Change in 80 percentile discharge following impoundment

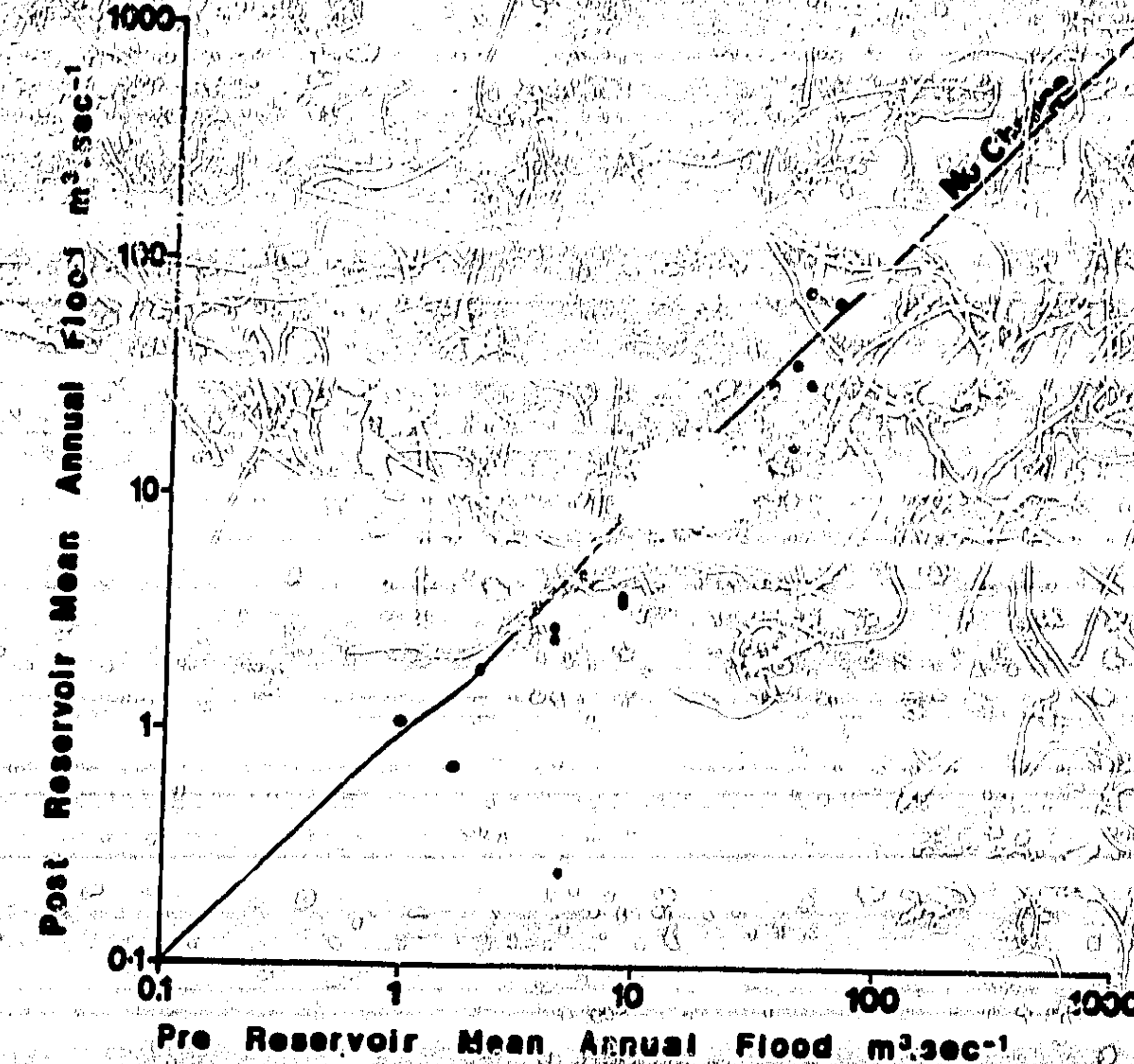


Figure 4.7 Change in calendar day mean annual flood following impoundment

record. Comparing hydrographs for the same period was essential to isolate the effect of impoundment from that due to differences resulting from wetter or drier than average periods. For the purposes of this analysis, spates greater than twice the average daily flow (2xADF) and five times the ADF (5xADF) were extracted from the hydrographs. Only independent spates were extracted from the record and were defined as being independent if the discharge dropped below the ADF between events.

The number of spates occurring after impoundment, as a percentage of those which would have occurred naturally, are shown in Figure 4.8. For those spates greater than 2xADF there has been a significant reduction in the number of events following impoundment. For the 8 sites used in the analysis, the average percentage of spates after impoundment was 30.5% of the natural value. However, there were large differences between sites with Eyebrook Reservoir retaining more than half the number of spates (51%) following impoundment, while Darwell Reservoir retained only 6%. For those spates greater than 5x ADF impoundment has also resulted in a reduction in the incidence of spates. Again there were large differences between sites with Ladybower Reservoir retaining 67% of these larger events while Darwell Reservoir retained only 2%.

The differences between sites are mainly attributable to the varying amounts of reservoir spill which occur. Figure 4.9 shows the relationship between the change in the frequency of spates and the reduction in mean discharge (equivalent to the net yield) following impoundment. It can be seen that the greatest reduction in the frequency of spates occurs downstream of reservoirs where the net yield is large in relation to the natural mean flow. These are, of course, reservoirs with relatively large capacities having long critical periods with infrequent occasions when they are full and spilling.

It can be seen that the effect of impoundment on the number of spates immediately below the reservoirs is significant. On average the incidence of spates was only 30% of that which would have occurred in a natural river. The implications of this reduction may be an important consideration when assessing compensation flows if the reservoir is on a river with an important fisheries interest. The results shown here are for illustrative purposes only and are based on the complete annual hydrograph. For an evaluation of the effect of impoundment on fish migration, a selective analysis would be carried out on those months known to be important.

4.4 Relationship between compensation discharge and low flow frequency

The comparison of the 95 percentile discharge before and after impoundment described in section 4.2 was based on flow data below 20 reservoirs. However, the choice of reservoirs studied was controlled entirely by the availability of gauged and naturalised flow data. It is possible that the data set is not representative and it was therefore considered necessary to carry out a wider study based on a larger number of reservoirs. This was achieved by estimating the 95 percentile discharge at ungauged sites immediately below 155 reservoirs using techniques described in the Low Flow Studies Report (Institute of Hydrology, 1980). This required the estimation of the natural mean discharge based on a simple water balance using catchment area, rainfall, actual evaporation and an estimate of the Baseflow Index (BFI). The 95 percentile discharge can be calculated from the BFI which is itself estimated at the ungauged site from catchment geology. It was not possible to estimate the post reservoir discharge (because of the absence of discharge data) and so natural flows were compared with the statutory compensation discharges.

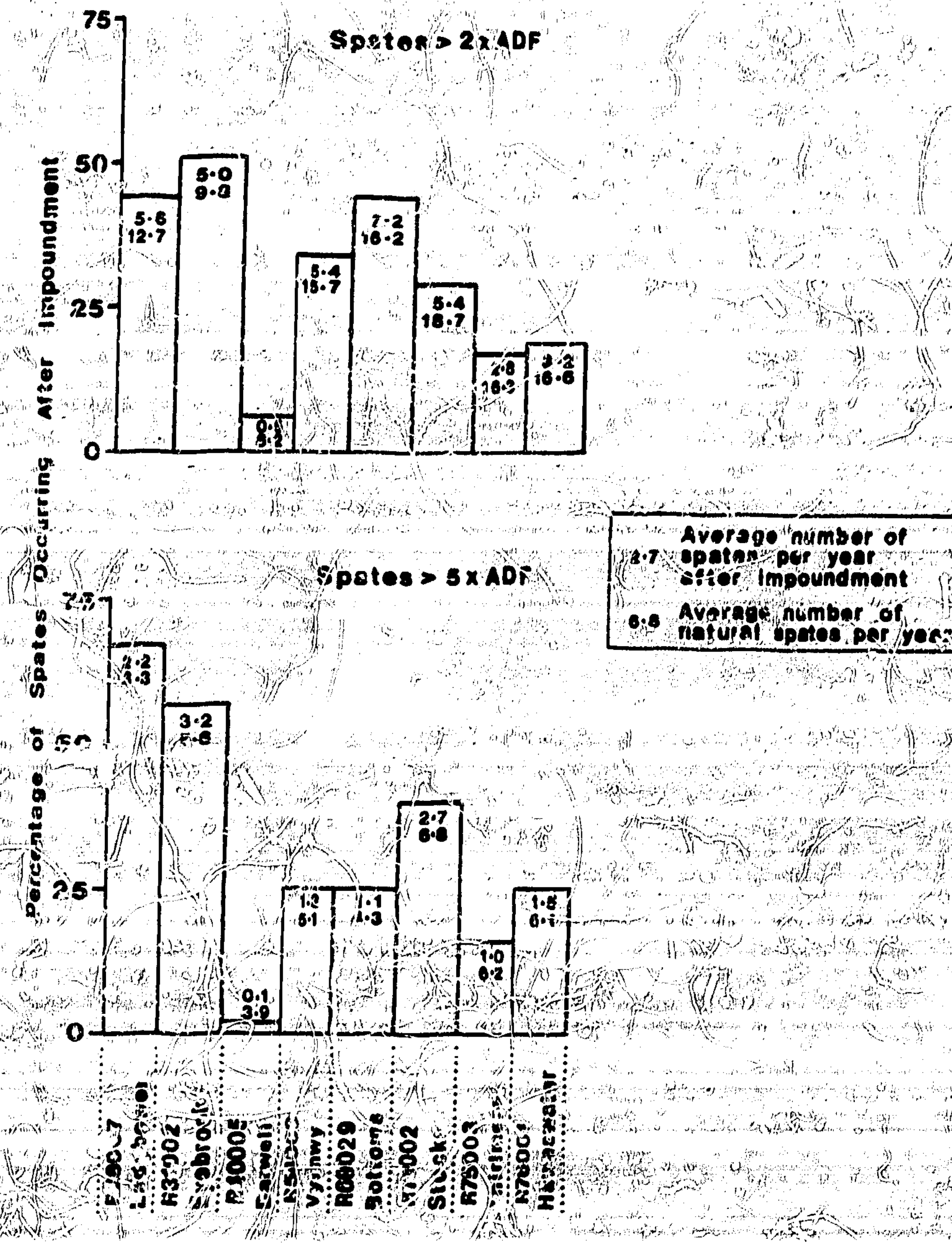
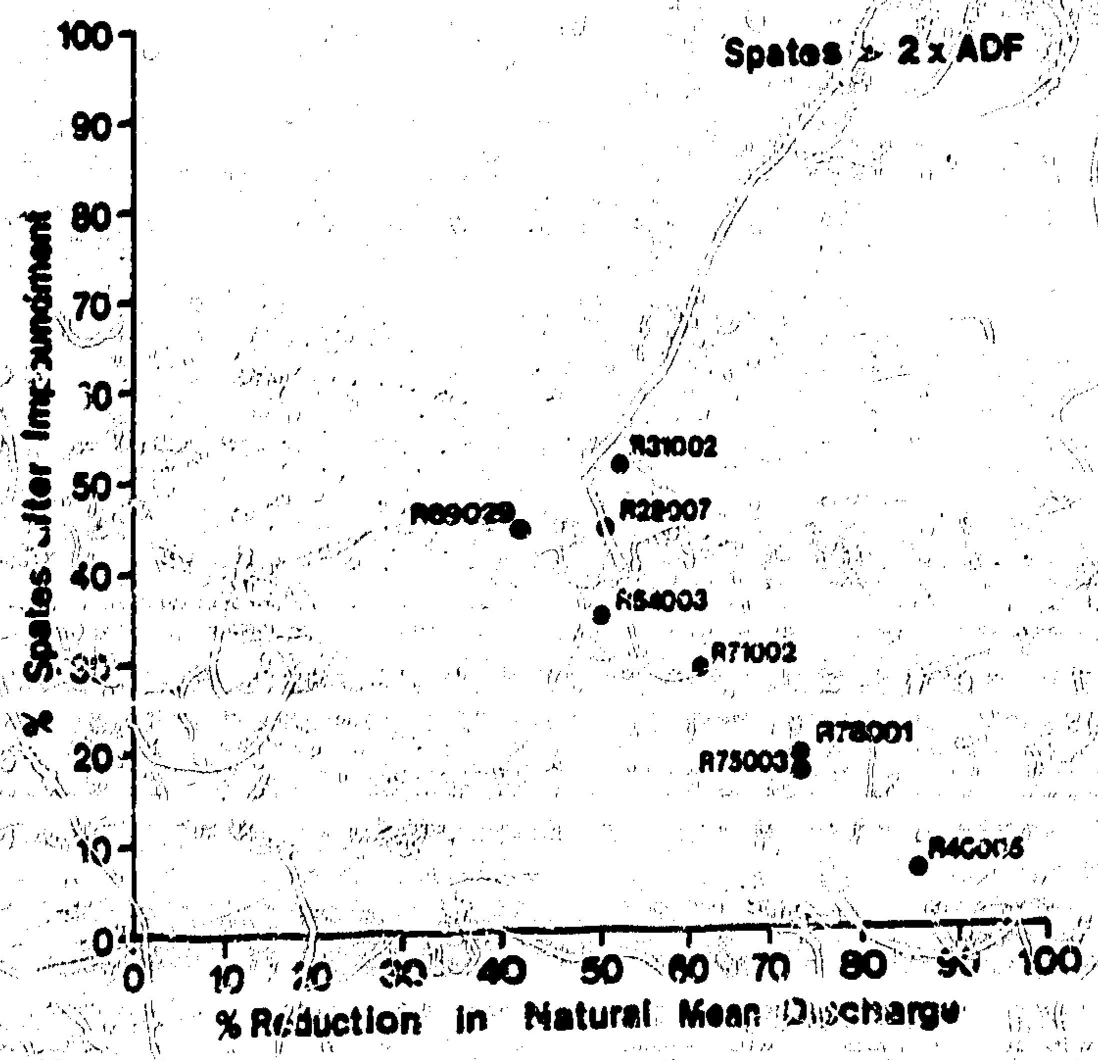


Figure 4.8 Change in number of spates following impoundment



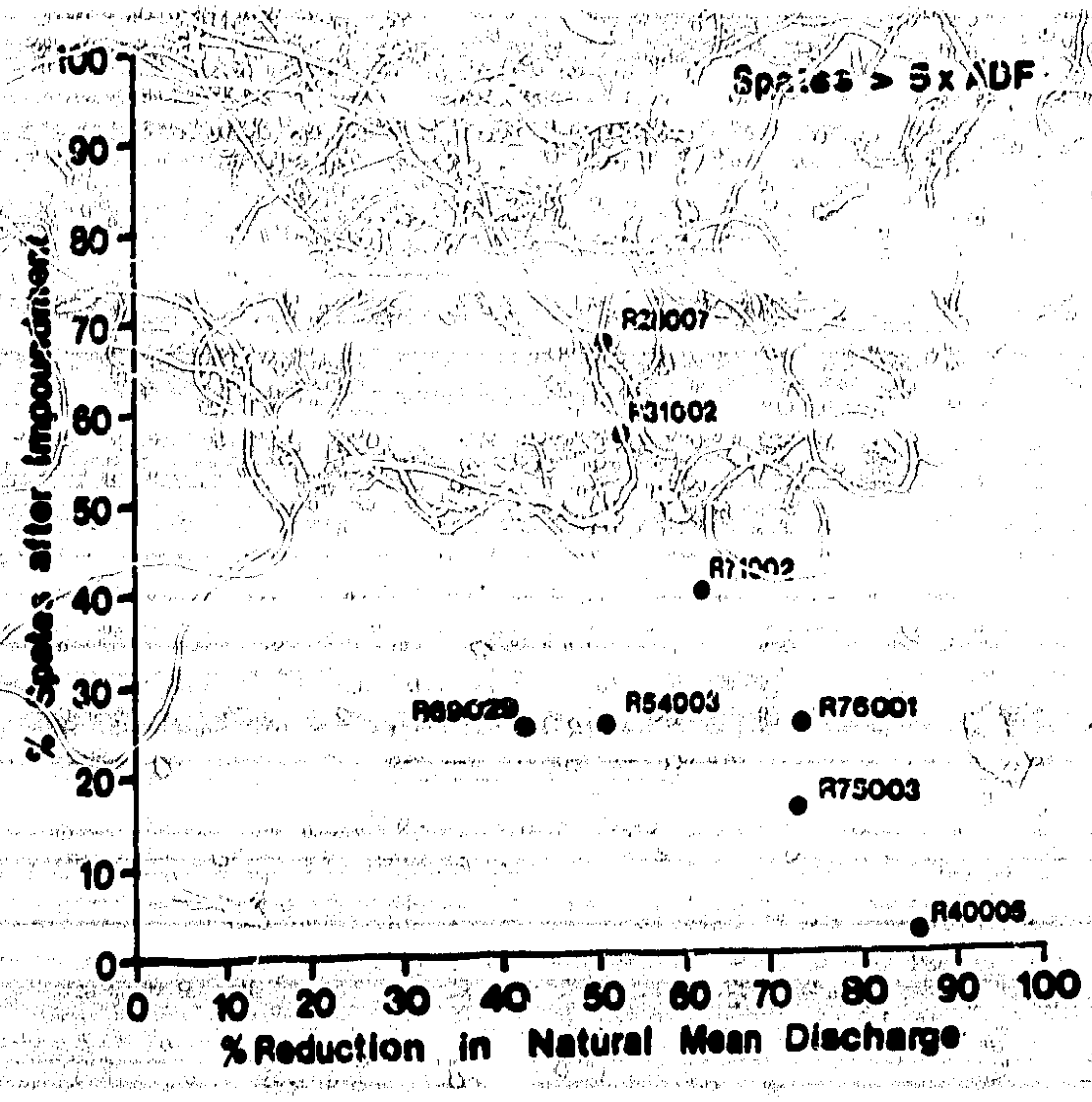


Figure 4.9 Relationship between reduction in average discharge and reduction in spates

Figure 4.10 shows the results of the comparison of compensation flows with the natural 95 percentile discharge. For 155 sites Q95 was estimated as outlined above and at 28 sites it was calculated from pre reservoir gauged flows or naturalised discharge data. Although there will be errors associated with individual estimates of Q95 these will not affect the overall distribution of the plotted points. Compensation only reservoirs often appear to make large releases compared with their natural inflow, but are usually being operated in conjunction with a supply reservoir sited on an adjacent tributary. These reservoirs (6 sites) have been excluded as have those reservoirs with zero compensation flow (32 sites). As with earlier comparisons of pre and post reservoir Q95's, it can be seen that there is a very wide scatter of points. Particularly noteworthy are the large number of sites with compensation flows substantially in excess of the estimated pre reservoir Q95. The figure also shows that the set of reservoirs with flow data available do not include schemes with the most generous awards. The mean 95 percentile preimpoundment discharge for all sites was 14.0% of the natural ADF and the mean compensation flow was 17.7% of the natural ADF. Thus compensation flows are approximately 22% higher on average than the natural 95 percentile low flow discharge.

4.5 Decrease in artificial influences downstream of reservoirs

Any changes to the flow regi[illegible] immediately below the dam and decrease downstream as [illegible] natural inflows increase. If less than 10% of a catchment [illegible] it is difficult to measure the changes in flow regi[illegible] the reservoir impoundment. This is a result of [illegible] errors in measuring river flows particularly in drain[illegible] also because any changes in flows are within the natural year [illegible] variability of the flow regime. It is even more difficult to [illegible] predict the environmental consequences of any change in discharge pattern when less than 10% of the discharge is being influenced. Any beneficial effects of compensation releases will therefore be at a maximum near the dam and can be considered negligible when the reservoired area is less than 10% of the total area considered. The only exception to this is if the scheme is operated such that very large releases were made for perhaps one or two months in the year with zero or negligible releases for the remainder of the year.

It is therefore proposed that the benefits of any release can be related not only to the size of release but also the length of river which is receiving a significant benefit. This has been indexed by identifying the incremental increases in natural discharge below 24 reservoirs. For each reservoir the natural average flow at and downstream of the outfall was estimated either from flow data or, in the absence of discharge records, by using a simple catchment water balance. Choosing sites upstream and downstream of major tributaries it was possible to relate distance from the reservoir measured from 1:50000 scale maps with incremental discharge. At each downstream site the ratio

$$R = \frac{\text{ADF site}}{\text{ADF reservoir}}$$

was calculated and plotted against distance downstream of the dam.

Figure 4.11 shows the results for two reservoirs. In the case of Lamaload reservoir it can be seen that a distance of 20 km below the dam is subject to a significant reservoir influence. In the case of Lindley Wood reservoir less than 5 km of river reach is significantly influenced by the compensation release before a major river is joined and the natural

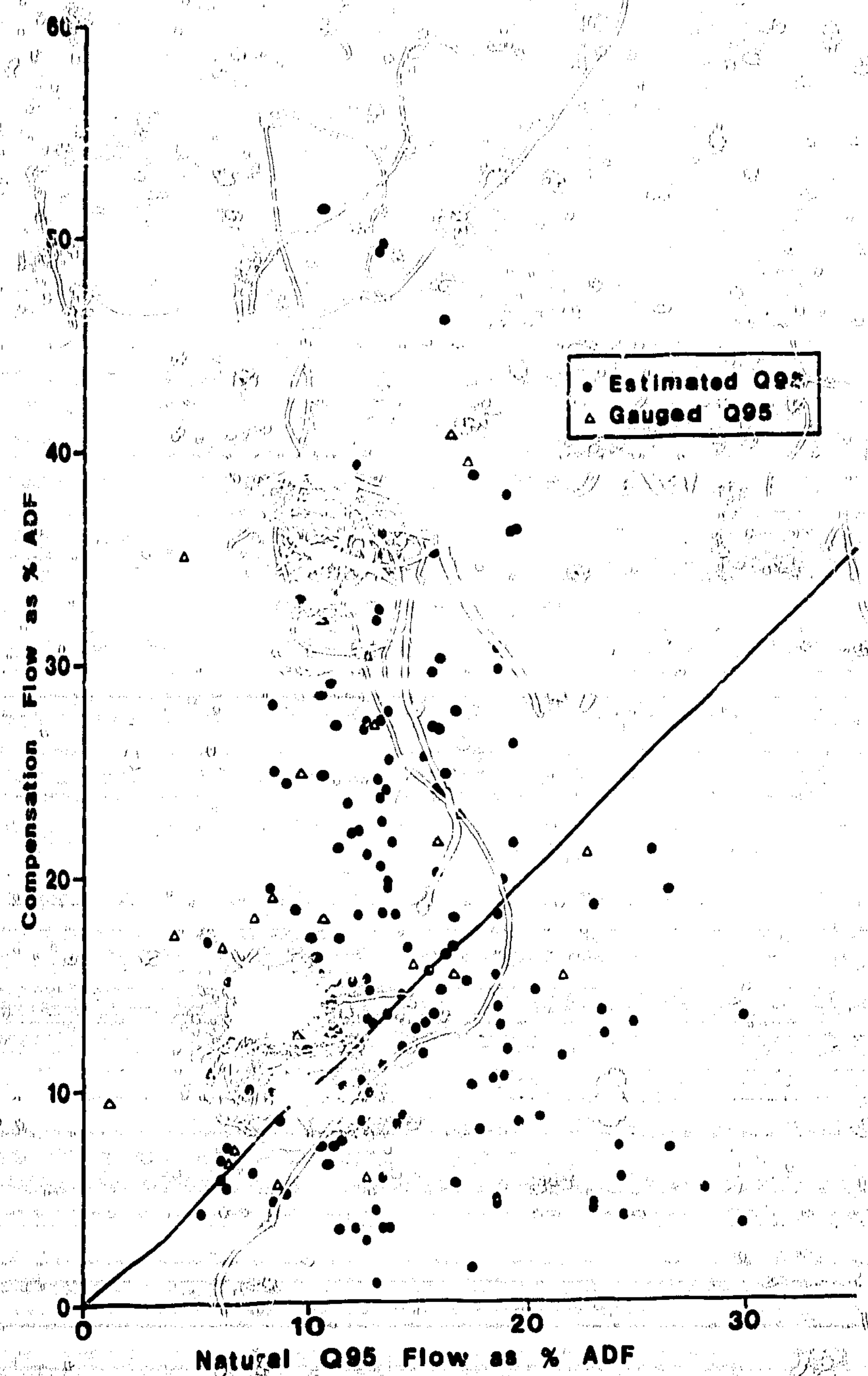


Figure 4.10 Relationship between compensation discharge and natural low flows

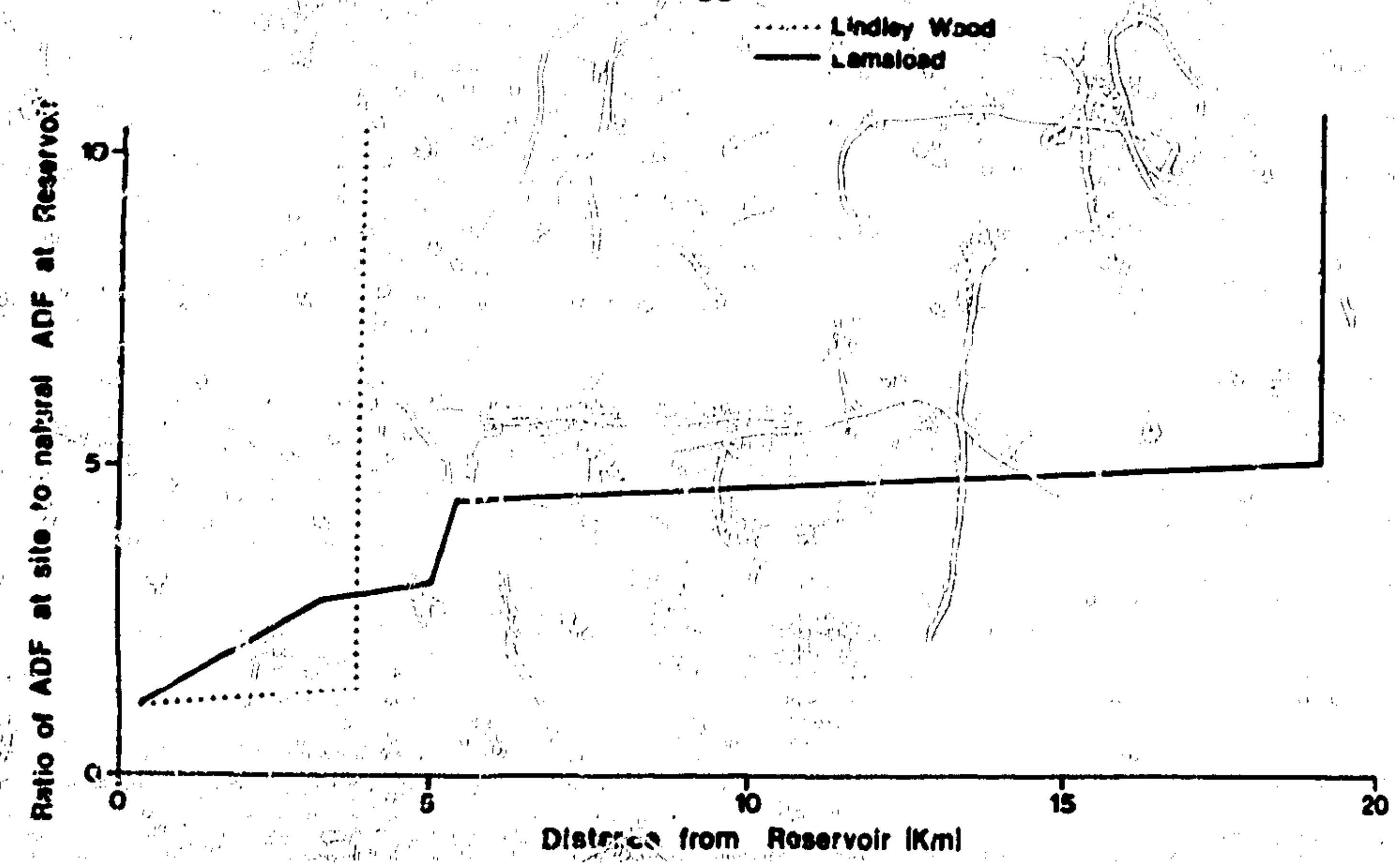


Figure 4.11 Increase in discharge with distance downstream of reservoir.

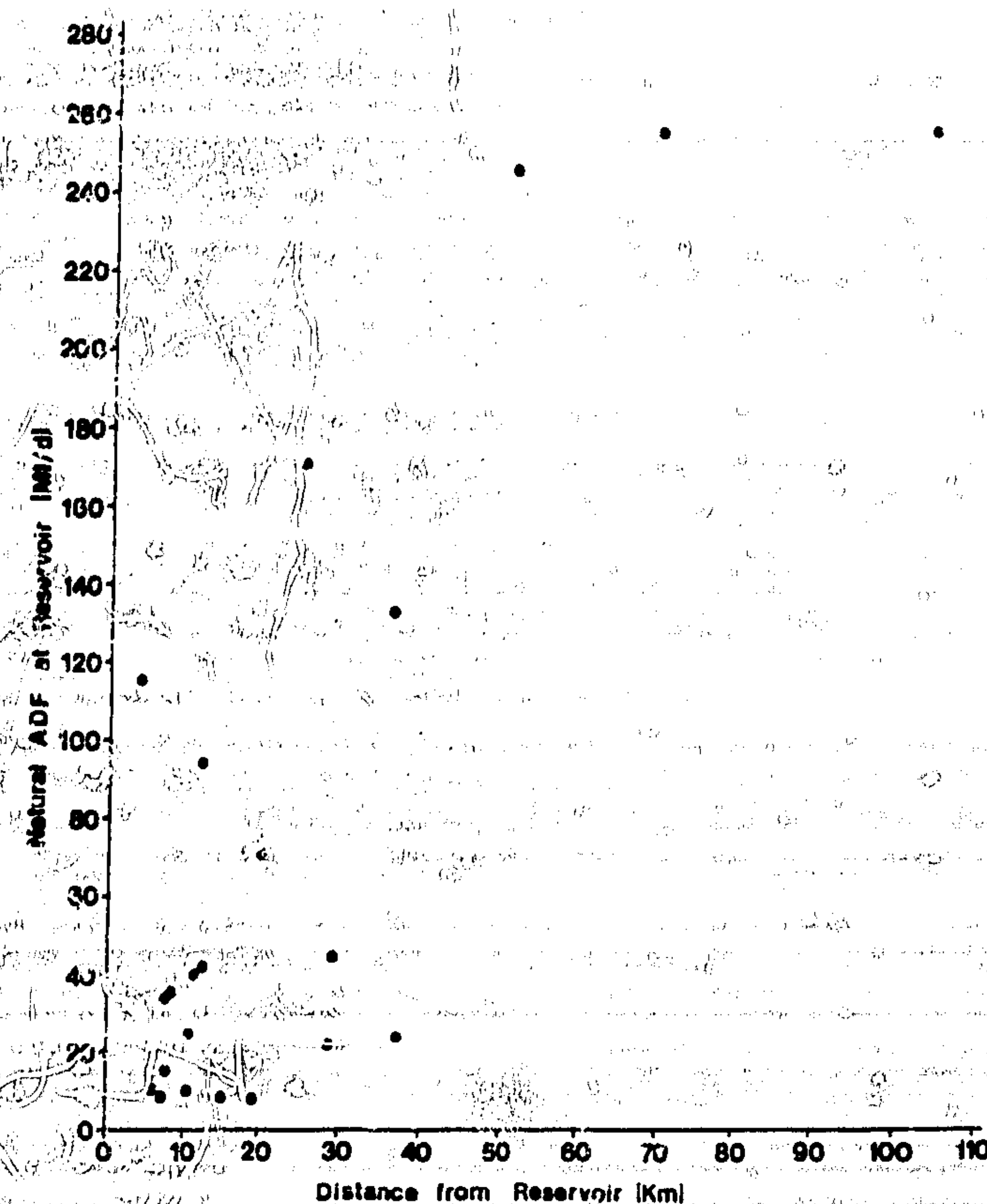


Figure 4.12 Relationship between natural ADF at reservoir and distance from reservoir when discharge has increased by more than ten times.

flow is more than 10 times that at the reservoir outfall. The study of 24 selected reservoirs covering sites in 4 Water Authorities identified large differences in the relationship between increase in discharge and distance downstream of the dam. Much depends on whether the reservoir is sited on a short tributary of a large river or whether the river downstream of the reservoir is joined only by small tributaries. Figure 4.12 shows that rivers with a high natural discharge at the reservoir outfall may not increase the flow by a factor of 10 for a distance of over 100 km, whilst those with a lower natural flow especially if they are only a short distance upstream of a major river will reach this point in 10 km or less. It is suggested that the length of river receiving a significant benefit from the compensation discharge should be a factor that is considered when setting compensation flows. This can be most accurately determined by deriving Residual Flow Diagrams for the river below the dam. A very thorough account of how to derive these diagrams is described in Pirt and Douglas (1980).

5. RELATIONSHIP BETWEEN RESERVOIR YIELD AND COMPENSATION FLOWS

5.1 Constant release

The gross yield of a reservoir is the sum of the net yield which is used for water supply purposes and the compensation discharge. Any constant increase in the compensation flow will result in a lower net yield for a given storage capacity and probability of failure; conversely any reduction in compensation flow would enable increased abstractions for supply purposes to be made. For the 152 reservoirs examined in the survey of reservoir yields (section 3.4.2) the total gross yield to supply was 7284 Ml/day and total compensation discharge was 1626 Ml/day. Thus approximately one fifth of the aggregate gross yield is used for compensation purposes.

5.2 Seasonally varying release

The effect of introducing seasonally varying compensation flows on the yield of a reservoir is determined by the reservoir storage, net yield and pattern of releases. These factors are site specific and require a reservoir simulation exercise to be carried out in order to assess the water supply implications of a proposed scheme which incorporates seasonally varying flows. However, it is possible to illustrate the sensitivity of seasonally varying compensation flows on the net yield of a hypothetical scheme.

A storage yield analysis was carried out on the flow record from a 9.1 km^2 catchment area of the Pennines. (Burbage Brook gauged at Lower Burgage). The record from this site is used for illustrative purposes only and whilst it is representative of upland reservoir sites the analyses would have to be repeated using local flow data for other locations in the U.K.

The storage requirement S_i needed to maintain a net yield Y was calculated from:-

$$S_{i+1} = S_i - Q_i + C_i + Y$$

where Q_i is the gauged daily inflow to the reservoir and C_i is the compensation discharge. The value of S_i will increase during a drought and decrease when 'reservoir' inflows exceed outflows. The 'reservoir' will spill when S_i is negative, in which case S_i is reset to zero. The maximum value of S_i, for any drought event, is thus the storage needed to just maintain the given yield. This simulation is carried out for the complete record and a series of S_i, the annual maximum values of S_i are extracted.

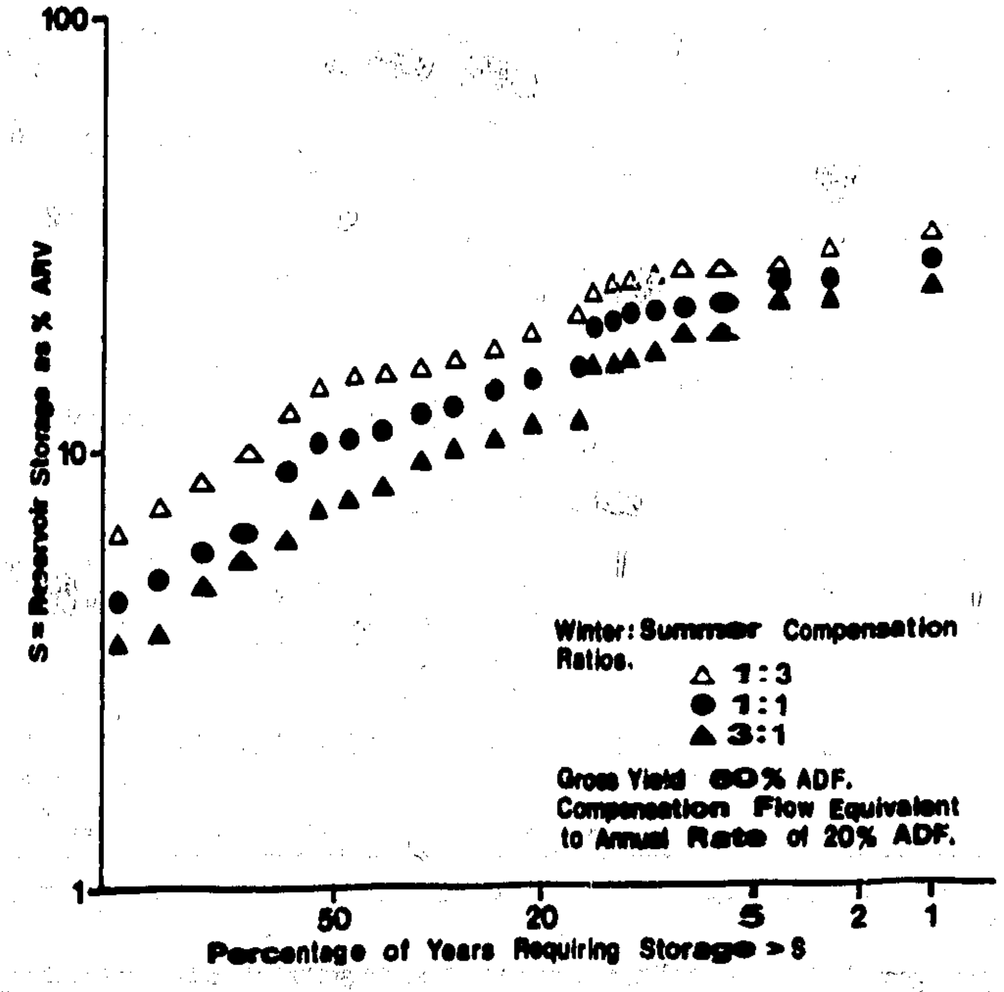


Figure 5.1 Relationship between storage and probability of failure for different seasonal patterns of compensation flow

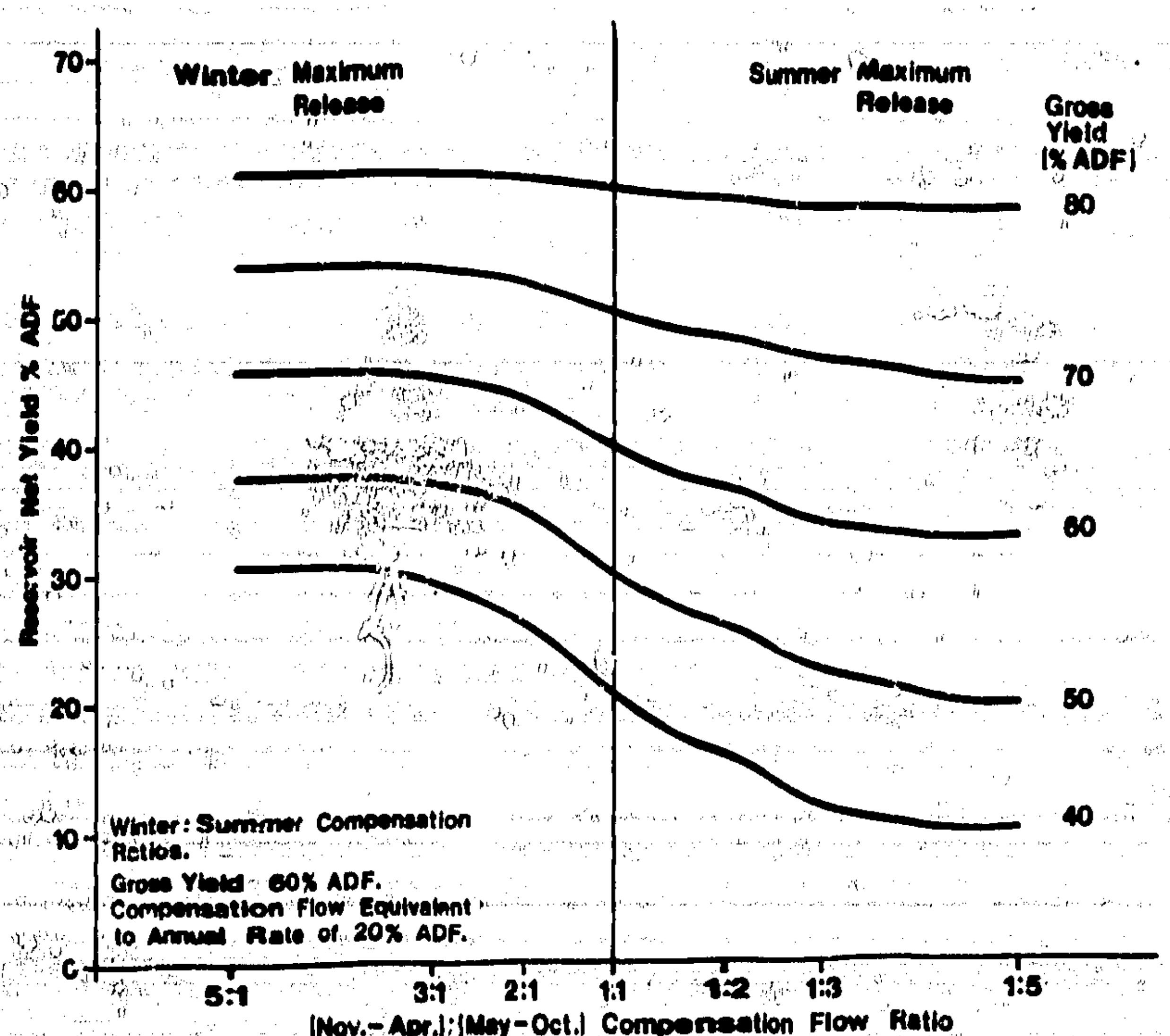


Figure 5.2 Relationship between net yield and seasonal compensation flow

These values are ranked from the smallest (j=1) to the largest and the non-exceedance probability F_j is calculated using the Blom plotting position:-

$$F_j = \frac{j - 0.375}{n + 0.25}$$

where n is the number of years of data. Figure 5.1 shows a plot of the storage requirement S_j against percentage exceedance on log-normal probability paper for three different compensation flow release patterns. The yield is expressed as a percentage of the average daily flow (ADF), and S_j as a percentage of the annual runoff volume (ARV). This facilitates comparison of storage yield relationships for catchments with different average flows. A smooth curve may be drawn through the points on Figure 5.1, and the storage required to maintain a yield with a given probability of failure may be estimated.

For each of the three simulations the gross yield was set at 60% of the average discharge (ADF) with a constant net yield of 40% ADF and compensation release equivalent to a constant annual release of 20% ADF. One of the plots is produced with a constant release of 20% ADF, the second with a ratio of winter to summer compensation flow of 3:1 and a third with a ratio of winter to summer of 1:3. Summer was defined as the period May to October and winter November to April. An example of the net yield and compensation flow for the winter maximum release with discharge expressed as a % ADF is as follows:-

	J	F	M	A	M	J	J	A	S	O	N	D
Net yield	40	40	40	40	40	40	40	40	40	40	40	40
Compensation	30	30	30	30	10	10	10	10	10	10	30	30

Simulations were repeated with different ratios of seasonal compensation flows and for gross yields of 40, 60 and 80% ADF. In each case the compensation flow was equivalent to an annual release of 20% ADF - close to the national average of reservoirs in the UK of 18.6% ADF (Chapter 3). For each of the three gross yields the storage required to maintain the net yield and a constant compensation flow with a 5% probability of failure was estimated. These storage values were then used to estimate the net yield for each of the different seasonal patterns of compensation releases but for the same gross yield and probability of failure. The results are shown on Figure 5.2.

It can be seen that the yield of reservoirs with small storages and hence low net yields are very sensitive to the seasonal distribution of compensation flows. For example, for a reservoir with a gross yield of 40% ADF having an annual compensation flow of 20% ADF distributed with a winter to summer ratio of 1:3, the net yield is reduced from 20% ADF (with a constant release) to 11% ADF. If the winter release is three times the summer value then the net yield is increased from 20% ADF to 30% ADF even though the total volume of compensation water released remains the same. It can be seen from Figure 5.2 that reservoirs with larger gross yields and therefore storage capacities are less sensitive to seasonal changes in compensation discharge.

Figure 5.3 illustrates the sensitivity of reservoir yield to different release patterns. The figure shows the depletion of a hypothetical reservoir subject to the inflow sequence of the Burbage mean daily flow

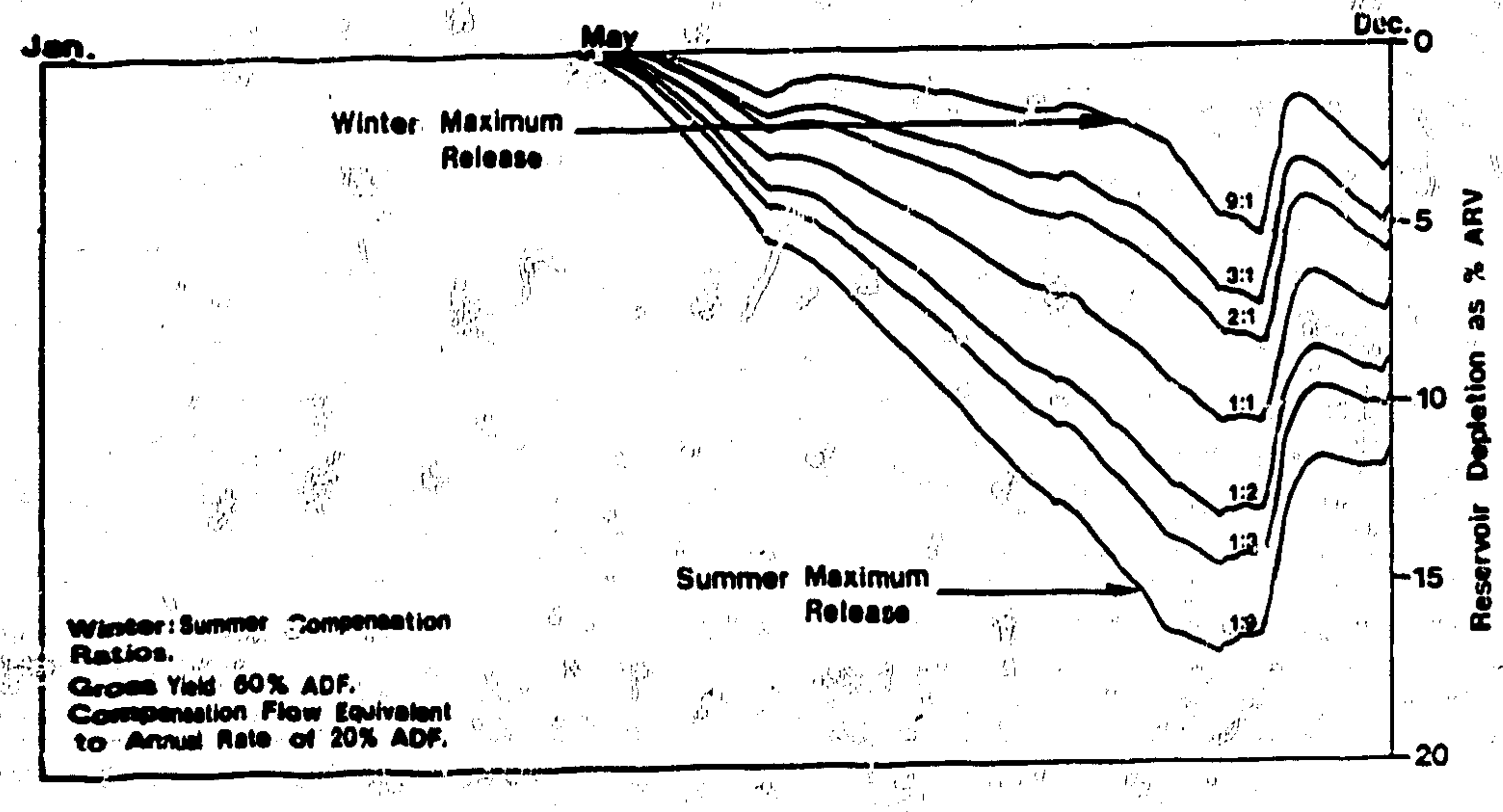


Figure 5.3 **Reservoir depletion for winter:summer compensation ratios as shown.**

series of 1975. The reservoir behaviour has been simulated with a net yield of 40% ADF and a compensation flow of 20%, for a range of winter:summer compensation flow ratios. It can be seen that with a summer compensation greater than the winter, reservoir levels are drawn down much lower than when compensation flows are constant. This results from the total demand (compensation flow + net yield) being greater when the natural inflows are lower. In contrast, with a winter maximum release, total demand is at a maximum when inflows are at a maximum and thus the depletion of reservoir storage is lower.

The storage yield relationships derived above are based on a very simplified reservoir simulation. In practice, the demand on the reservoir may vary seasonally and rationing would be introduced prior to reservoir failure. In addition many reservoirs are integrated into complex water resource schemes using sources with different storage characteristics. However the results do illustrate that some benefits to the yield of a reservoir can be achieved by maintaining the same annual volume of compensation flow but introducing variable releases. Conversely benefits to the river below a reservoir may result from the introduction of higher compensation flows for some months of the year which if offset by lower releases in other months will result in little change to the yield of the reservoir. It is recommended that if seasonally varying flows are required to meet water quality or fisheries objectives then a simulation study of the impact on reservoir yield is carried out.

6. COMPENSATION FLOW AND RIVER BIOLOGY

6.1 Introduction

Development of new water resource schemes and alterations to existing compensation flows require an assessment of the impact of changes on the flow hydrograph and the biology of the river. The construction of a dam on a natural river will obviously have profound implications for river ecology. The physical presence of the dam will be the major influence acting, for example, as a barrier to upstream migration of fish and possibly inundating valuable spawning and nursery grounds in the headwaters (Petts, 1984). A second influence will be the change in both the quality and quantity of the downstream flow regime and this will affect the river ecology in two main ways:

(i) by the release of stored water which may be of a different temperature, chemical composition, suspended sediment and organic content to river water

(ii) by reducing flow variability with reduced flood flows and constant low flows.

These two effects may be difficult to distinguish since organisms integrate all signals from the environment and react accordingly (Edwards & Crisp, 1980). Changes in the flow regime and consequent alterations in the nature and stability of the substratum and drift, will in turn influence the productivity, diversity and composition of the stream benthic community. This is extremely important to the total functioning of the stream ecosystem as it provides a major source of food for fish and other organisms.

Recent reviews (Ward, 1976; Brooker, 1981; Armitage, 1984) have shown that regulated flows can affect the river biota in a variety of ways, depending on the extent and type of regulation. Most attention has focussed on the effects on fish because of their [illegible] commercial value. In addition, as Blezzard (197[illegible]) points o[illegible] the UK most suited to water conservation and hydroelectri[illegible] also those which produce the main weight of migratory fish. A conflict of interest therefore exists, and increasing attention is being paid to reconciling the two interests. In this chapter, the main effects of changes in the flow regime on fish life will be summarised. This is not presented as an exhaustive literature survey and the reader is referred to Milner et al (198[illegible]) and the results of more detailed studies by the Freshwater Biological Association in Teesdale (Crisp, 1985 unpublished).

Although fish are of more immediate interest in relation to the problems of setting compensation flows, investigations of invertebrates have some distinct advantages. The invertebrate fauna is more diverse and will respond rapidly to a wide range of environmental variables. It should therefore show some response to relatively small changes in the flow regime and provide one of the best indicators of prevailing and past ecological conditions. Other practical advantages of studying invertebrates are the relatively cheap and easy sampling techniques involved.

With these considerations in mind, the Freshwater Biological Association was commissioned by the Department of Environment to examine the macroinvertebrate fauna below 29 reservoir sites in the UK.

Compensation releases varied considerably at the 29 sites enabling a range of flow regimes to be studied. The aims of the study were, firstly, to relate below reservoir faunas to compensation flows and other environmental variables and secondly to compare faunas below reservoirs to existing data on natural stream faunas. This work is summarised in section 6.3, and described in detail in Appendix A4.

6.2 Fish

6.2.1 Introduction

The British salmonid species comprise Atlantic salmon (Salmo salar L.) and the trout (Salmo trutta L.) in its resident (brown trout) and migratory (sea trout) forms. The migratory salmonids have the most critical flow requirements, because of their need to traverse estuaries at least twice during their life cycles (MAFF/NWC, 1980). Non migratory salmonids and coarse fish are less susceptible to hazards although the spawning and egg stage is often critical. Flow conditions suitable for migratory salmonids will thus generally be acceptable for non migratory types. Briefly the life history of salmonids is as follows:-

(i) All salmonids spawn in clean gravel beds in the headwaters of rivers during the autumn. Eggs are laid in a series of egg pockets in structures termed 'redds'. The egg develops within the gravel and hatches to give an alevin. The alevin initially lives within the gravel feeding on food reserves in its yolk sac. When this is depleted it emerges from the gravel to enter the free swimming or fry stage and feeds from the river.

(ii) The fry quickly establish territories, and as a consequence supernumerary fry die or are dispersed downstream, and, in populations at high densities, the rate of mortality and/or dispersal is density dependant.

(iii) After 1-3 years in the river, the migratory salmonids, namely young salmon and sea trout, become smolts and after undergoing physiological changes migrate to sea. Brown trout remain within the river system.

(iv) In comparison with the freshwater development, information on the marine life cycle is less well documented. Some salmon return to their native river to spawn after only one year, others remain in the sea for up to four years and may grow to large sizes. Spawning migration takes place in certain months of the year according to the location of the individual river system with the particular occurrence of migration being discharge related. Weirs and waterfalls may have to be surmounted on their long journey upstream. After spawning most salmon die, although many sea trout survive and spawn again.

6.2.2 Flow requirements of fish

Changes in flow result in changes in velocity, depth, width, wetted area and these together with some of their consequences, such as transport of food and dissolved oxygen have important effects on fish. This makes it difficult to establish causal relationships between fish behaviour and particular aspects of the flow regime.

Salmonids have a range of flow requirements related to the different stages in their life cycle. There must be sufficient flow for survival, to stimulate spawning, to protect the feeding habits of fry, and for both upstream and downstream migration. It is also important to maintain a generally healthy river.

Survival

It has been argued that minimum acceptable conditions for fish life cannot be expressed in flow terms alone. Fish stress is often related to water temperature, BOD, ammonia and other factors, only some of which are a direct result of flow (Petts, 1984). Also, minimum conditions required vary considerably between life cycle stages.

Spawning

Spawning gravels should ideally be clean and relatively stable and sufficiently open to allow water to percolate through to keep the eggs oxygenated. Work on the rivers Lune, Avon, Frome and Welsh Dee reported by Brayshaw (1966), showed that salmon spawn naturally at depths of 0.3 to 0.8 metres and at velocities of between 0.44 to 0.97 m/sec. At velocities above 3.66 m/sec spawning is inhibited, as salmon are unable to maintain sustained swimming effort.

The Freshwater Biological Association (Crisp, 1985) are carrying out a detailed investigation on silt transport and the deposition and survival of intragravel stages of salmonids, and the associated problem of gravel movement and egg washout. In general, both extreme high and low flows can have deleterious effects on the intragravel stages. High flows may lead to washout of eggs and alevins from the gravel beds, while prolonged low flows may allow sediment to seal gravel interstices and reduce oxygen supply to the redds. Sudden fluctuations in flow are clearly not desirable, as they may leave salmonids (in the intragravel stages) stranded. Results suggest that salmonids generally avoid spawning in water shallower than their own body depth or at velocities less than approximately 0.2 m/sec. Disturbance of gravel and hence washout of redds was found to be most severe up to a depth of approximately the mean grain size.

Reservoir inundation can seriously deplete fish stocks by reducing the area of spawning grounds eg Loch Garry in Scotland, though the salmon may find alternative spawning grounds as at Llyn Celyn, N. Wales. Here more than 6 km of first class spawning grounds on R. Dee were lost and salmon have adopted small unregulated tributaries downstream of the dam for spawning (Armitage, 1979).

Downstream migration

A river can support only a certain density of fish, as fry establish territories (Le Cren, 1961), with the excess being forced downstream into more unsuitable areas, with increased mortalities. Thus the stock of salmonid fish is more likely to be determined by the area of fry rearing ground as much as by the number of spawners. Research by the Freshwater Biological Association (Crisp, pers. communication) suggests that on some upland streams, extreme temperature and flow variations may reduce egg densities to suboptimal levels at which this density dependent mechanism for controlling fry populations no longer operates.

The effect of water velocity on the downstream movement of recently emerged salmon and trout parr in experimental channels has been studied in detail by the Freshwater Biological Association (Crisp, 1985). The rate of downstream movement of trout was highest at velocities of 0.4-0.7 m/sec while the maximum rate of salmon movement occurred at low velocities of 0.07 m/sec. This suggests that salmon utilise low velocities and move downstream to avoid them. The rate of dispersal was not linked to a particular stage of development, but seemed to continue until an appropriate population density had been reached.

Upstream migration

Both resident and migratory adult salmonids migrate upstream in their natal river system to spawn. Migratory salmonids come in from the sea and therefore must traverse almost the whole length of the river; resident salmonids move much shorter distances within the river system.

The relationships between salmon movement, flows and other environmental parameters is still poorly understood, (Mills, 1981) and was considered a priority area of research by the Joint Freshwater Fisheries Advisory Committee (MAFF/NWC, 1980). The stimulus for migration is not thought to be due solely to the physical character of high flows (though most movement takes place at flows in excess of the average flow), but also the change in river chemistry or discoloration of water associated with it. Salmonids run at fixed times of the year in each river with, normally, a main run followed often by subsidiary runs. The effects of flow changes and other environmental factors are thus superimposed on this basic temporal pattern.

There seems to be conflicting evidence about the relationship between salmon runs and flow (Mills, 1981). Alabaster (1970), studying 6 years of fish count data for R. Coquet, Northumberland and other published data, found that salmon move at flows higher than the available median, but could find no preferred flow for all rivers. Stewart (1968, 1969) identified a migratory flow range from .008 cumecs/metre width to .018 cumecs/metre width of river. Peters et al (1973) found maximum migration occurred at flows between 0.5-4.0 times the average flow; Brayshaw (1966) quotes 0.7 to 1.5 times average flow. In complete contrast 10 years of fish count data on R. Frome (Hellawell et al, 1974) failed to show any relationship with flow. This chalk river, however, has a fairly constant, stable flow regime compared with the flashy, Pennine rivers examined by Stewart. The release of artificial freshets from a reservoir has been successful in stimulating the ascent of salmon in some river systems (Banks, 1969; Huntsman, 1945), but their value has yet to be proven scientifically. Natural spates are more successful than artificial releases and fish are known to move without freshets or even during reduced flows (Allan, 1967). Pyefinch et al (1965) regard freshets as useful only if they prolong the natural spate. However studies of the effectiveness of artificial flood releases are complicated by the varying numbers of fish which are available to migrate throughout the season. Less attention has been paid to the required size of peak flow, or duration or frequency of freshets. Most fish move on the recession rather than the peak flow (Stewart, 1968; Menzies, 1958; Huntsman, 1945) perhaps to avoid the high velocities and sediment movement associated with the peak of a spate.

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Provided flow rates are sufficient for migration, then other factors such as time of day, water temperature and turbidity will influence fish movement. Hellawell (1974) states that under clear river conditions movement is generally at night, while in turbid conditions salmon will move during the day. Both Stewart (1968) and Allan (1966) report increased movement at night, although light is required for the fish to ascend obstacles.

The upstream movement of resident salmonids is also seasonal and flow dependent. An attempt to relate upstream movement of mature brown trout for the period 1974-1980 to flows in a natural stream (Carl Beck - a tributary of R. Lune in Yorkshire) is described in Appendix A5. Trout were found to move up to spawning grounds at specific times of the year (92% from October to November). Although no distinct threshold discharge was found beyond which fish movement started, there seemed to be some relationship between upstream movement and daily mean or maximum flows. Over the migration period there was a clear increase in the probability of upstream fish movement for those days when the flow was in excess of 80% of the average discharge. In terms of total fish movement, 72% of trout moved when the flow was in the range [illegible] to 700% of the average discharge.

6.2.3 Attempts to set flows to protect fisheries

Attempts to quantify the varied flow requirements of fish have been relatively rare and confined to the more demanding requirements of migratory species. It is generally agreed that a single constant discharge cannot satisfy the varied annual requirements of migratory fish such as salmon, and a seasonally varied flow regime is preferred. Baxter (1961) proposed variable compensation flows below dams based on the seasonal needs of fish in 15 rivers in UK. His recommendations have been adopted on several Lothian reservoirs e.g. Fruid, Westwater. Seasonally varying releases are expressed as percentages of the average daily flow (%ADF) in order to provide adequate flow and bottom coverage for different sizes of rivers (see Table 6.1). He considered the minimum flow requirement

TABLE 6.1 SCHEDULE OF FLOWS PROPOSED BY BAXTER (1961) FOR ATLANTIC SALMON IN STREAMS OF SCOTLAND AND ENGLAND

Month	For the smaller rivers and streams % ADF	For the larger rivers % ADF	Remarks
October	15-12.5	15-12.5	During alternate weeks
November	25	15	
December	25-12.5	15-10	25 and 15 normally during first two weeks only
January	12.5	10	
February	12.5	10	
March	20	15	
April	25	20	
May	25	20	
June	25-20	20-15	During alternate weeks
July	20-15	15-12.5	During alternate weeks
August	15	15-12.5	During alternate weeks
September	15-12.5	15-12.5	During alternate weeks

Note: These schedules are not intended to be rigidly applied and require [illegible] incidence to suit the conditions of the particular case and season, e.g. variations in spawning times. This applies also to the rates of flow, which may require adjusting either way.

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to maintain healthy conditions for aquatic life, including the food supply of fry and parr, could be met by the dry weather flow, subject to a minimum flow of 12.5% ADF in dry periods. In addition Baxter suggested that for upstream movement in spring, salmon required flows of 30-50% and 70% of the ADF in lower/middle reaches and upper reaches respectively. These freshet releases would need to last for 18 hours only, of which 12 hours would be at the full rate, followed by 6 hours in which the flow was gradually reduced. His recommendations, though based on extensive fisheries experience have been criticised as being rather subjective (Fraser, 1975).

Stewart (1969) identified two critical flow bands to maintain a migratory fish stock, firstly a minimum flow or 'survival' flow, and secondly 'a migratory flow band' to induce and aid salmon migration. Preservation of this range of flows in which most fish movement takes place is therefore an important consideration in setting compensation releases for fisheries. Analyses of 5 years of fish count data from the Rivers Lune and Leven in Cumbria, N.W. England led Stewart to suggest a survival flow of 2.41 Ml/day/metre width of river with migration commencing at flows of 7.23 Ml/day/metre width reaching a maximum at flows of 17.3 Ml/day/metre width of river. Cragg-Hine (1984) analysing data from fish counters on other North West rivers confirmed Stewart's lower range of migration flows. He presents a plot of the frequency of occurrence of water level with the number of fish moving at each water level and suggests that fish actually move at flows less than their preferred flow, but this is still in excess of the modal flow of the stream. Such analyses of fish count data relate only to the free swimming stage, and are complicated by the lack of knowledge on the downstream availability of fish. This problem has also been acknowledged by Peters et al (1973) and others working with fish counters.

Fraser (1975) provides a comprehensive review of the extensive research in Western USA and Canada to set flow requirements for fish. The most widely used of these empirical methods is that developed by Tennant (1975). In recommending flows as a percentage of the mean discharge the method is similar in approach to that of Baxter (1961). On the basis of over 10 years of field research, Tennant recommends 10% of the average annual flow as a suitable short term survival flow, and 30% and 60% of the average for resident salmonids during October to March and April to September respectively.

Increased recognition of the conflicting interests on important fishing rivers in USA has led to the development of more complex computer simulation models for assessing 'instream flow requirements'. Numerous approaches have been developed, and Petts (1984) reports that in 1980, some 11 different methods were in use in the USA. Fraser (1975) outlines some of these earlier methods e.g. Oregon method in 1972. One of the most widely applied simultion models is the 'Incremental Flow Method' (IFM) developed by the Cooperative Instream Services Group of the U.S. Fish and Wildlife Service in 1976 and outlined by Wesche and Rechard (1980). It is now a legal requirement for setting instream flows in five western states of the USA and is used increasingly in Canada and New Zealand. The IFM model estimates the relative amount of physical habitat available, or weighted usable area (WUA) for various life stages of fish under different flow conditions. A hydraulic simulation model is used to predict depth, velocity, wetted area etc for different discharges in different reaches. From this the surface area represented by various depths and velocity criteria can be calculated (these areas need not be contiguous). Detailed field surveys relate fish occurrences to conditions of flow - namely depth, velocity, substratum and temperature, and flow preference curves can be

drawn up for different species and stages in the life cycle. The hydraulic and fisheries data are then combined in the calculation of weighted usable area from:-

$$WUA = \sum_{i=1}^{n} A_i C_i$$

A_i = surface area of stream section element
C_i = composite suitability of that element ie product of suitability of velocity, depth and substratum suitabilities
n = total number of elements being simulated

This exercise can be repeated for different species and stages in the life cycle, for a set of flow regimes, thereby building up a comprehensive picture of habitat suitability. The application of the method is based on the underlying assumption that fish biomass is proportional to weighted usable area. Scott (in press, 1985) working in New Zealand argues that this is not proven and that the model simulates changes in an index of fish habitat rather than fish populations directly. He also criticises aspects of the hydraulic simulation model.

Although the Incremental Flow Method makes necessary simplifications in relating flow regimes to fish populations, the modelling technique represents an important development on existing rules of thumb. As a result of the differences in climatic and hence hydrological regimes, and the fact that most N. American research relates to a different genus, the Pacific salmon of the genus <u>Oncorynchus</u>, it would not be possible to transfer results directly from N. America to Britain. However there is a clear need for a more objective approach to setting flow requirements for fishery purposes and this could be improved by developing the IFM technique in the UK.

6.3 <u>Invertebrates</u>

6.3.1 Introduction

Invertebrates are adapted to their environment and any alterations as a result of impoundment, for example, in temperature, flow, substratum, vegetation, food supply, water quality etc. will alter the composition and abundance of stream benthos. With so many interacting factors it is hard to establish causal relationships. Ward and Stanford (1979) identify temperature, flow and the substratum as the three dominant variables controlling macroinvertebrate distribution and survival. Temperature exerts its main influences on the rate of growth and development of biota, water quality affects the nutrient budget and flows affect the physical state of the substratum. However, sudden temperature changes may also result in a break in the life cycle.

The effects of flows are of prime concern here, although it is recognized that it is difficult to isolate this from other factors. Several literature reviews (Ward, 1976; Brooker 1981; Armitage, 1979) have summarised the effects of flow regulation, but there have been few attempts to establish causal relationships. It is generally agreed that a constant compensation flow regime, in excess of natural low flows, results in enhanced numbers or biomass of macroinvertebrates even when short-term fluctuations are imposed (Ward, 1976). In fact some periodic flushing is desirable to prevent settling of fines clogging interstitial spaces in the substratum. However, species capable of withstanding high flows may give way to those with lower flow preferences, thereby substantially altering the composition of benthos. According to Ward (1976), Diptera, Oligochaeta, Amphipoda and Gastropoda are usually favoured below dams; Trichoptera and Ephemeroptera may be enhanced or reduced, and Plecoptera are usually severely reduced. Observations by Armitage (1978) comparing the fauna below Cow Green reservoir with the unregulated adjacent tributary of Maize Beck, broadly confirm this. He noted increases of Oligochaeta, Chironomidae and Diptera below the dam and also large numbers of microcrustaceans (from reservoir water) which may provide an enriched food supply for fish.

Constant flows below the natural flow may result in severe reductions in wetted areas and hence reductions in overall productivity of the stream. The results of the stream drying up for even short periods can be catastrophic, although some species can survive in pools and under rocks for a short time.

The most detrimental flow regime is one with substantial, intermittent flow variations periodically exposing large areas of channel and leaving species stranded. Variations in velocity may destroy pool/riffle relationships and create bank instability (Armitage, 1984). Also very high flows (in excess of 2 m/s) result in scouring of the bottom with a consequent decrease in aquatic vegetation and loss of fine organic food material.

Attempts to establish flow requirements specifically for invertebrates are rare; Gore and Judy (1981) in Canada have adapted the 'Incremental Flow Method' to invertebrates and produced encouraging results. This approach has yet to be adopted in Europe.

6.3.2 FBA Study

The background and aims of the FBA study were set out in the introduction. The report is presented in full in Appendix A4, and summarised below.

1. Macroinvertebrate faunas (at family level) were sampled below 29 reservoir sites in UK, and at 4 control sites. All the reservoirs were of a direct supply type and released a wide range of compensation flows. Hydroelectric and regulation schemes and polluted sites were excluded from the analysis.

2. Pond net samples were taken downstream of the reservoir in spring, summer and autumn of 1983, and analysed in the laboratory to identify families and assess abundance. Environmental characteristics were recorded in the field and/or from maps, and water quality data were provided by Water Authorities and Purification Boards.

3. Data from all seasons were combined and analysed statistically using ordination and grouping techniques. 70 families were recorded from the 33 sites, with no significant seasonal variations. No obvious relationships could be found between the fauna and compensation flows.

4. Data were combined with existing FBA data for 300 unregulated sites and divisive techniques, such as two way indicator species analysis (TWINSPAN), used to see if regulated and unregulated faunas were different. TWINSPAN uses indicator species to divide the data two ways into successively smaller groupings. The majority of regulated flow sites occupied two adjacent groups, indicating their similar faunas, despite being subjected to different compensation releases.

5. There were no noticeable detrimental effects of regulation, at a family level of identification.

6. It was notable that the regulated sites tended to group with natural sites on different rivers, which are flatter, at a lower altitude and located further from the source. This is a clear indication of the stabilising effect of compensation flows, which may lead to an increased abundance of certain families.

It is therefore clear that within the range of compensation flows experienced in UK, the invertebrate fauna is remarkably resilient to change. The main effects are a change in family composition and abundance.

7. SEASONAL FLOW DISTRIBUTION

7.1 Introduction

The survey of compensation flows indicated that the most common form of variable compensation flow release was based on a simple division of the year into a summer and winter period. This policy was popular in setting awards for reservoirs on rivers with an important fishing interest and has been adopted on many Scottish schemes and some in England and Wales. For the majority of reservoirs the compensation discharge is higher in the summer than the winter months providing a higher discharge when the stress on fish population may be at a maximum. However, the choice of particular flow levels at different times of the year would appear to be arbitary.

By permitting larger releases in critical months and conserving water for supply purposes for the remainder of the year, seasonally varying compensation flows can provide considerable benefits compared to a constant release. The natural seasonal variation in flow frequency provides useful information on which to base any assessment of seasonal releases. For example the determination of the frequency of flows at maintained flow points will enable estimates to be made of the releases required to safeguard fisheries, water quality or existing abstractions. If increases in summer flows are recommended and it is essential to maintain the net yield of the reservoir, then lower releases will be required in the winter months (Chapter 5).

It has been argued that compensation releases should where possible follow the natural cycle of river flows. If this policy is adopted then the seasonal variability of low flows could be used to set a varying release pattern e.g. by adopting the natural 95 percentile discharge for each month of record. Although this may provide a convenient method for setting reservoir releases in practice the maximum benefits of compensation water are more probably realised in the summer months when natural flows are at a minimum.

Discussions with the water industry indicated that while the seasonal variability of flows could only occasionally be used to set compensation flows directly, the information would assist the decision making process. Although the frequency of discharge in cumecs would be used for estimating the dilution of effluents; depths, velocities, wetted perimeter and cross sectional areas may be more appropriate information to support invertebrate or fishery surveys. Such variables can be derived from the discharge hydrograph provided hydrometric field surveys are carried out for the reaches of interest. By estimating seasonal flow duration curves the frequency of discharge and related variables can be conveniently summarised. They illustrate, for any month (e.g. all Julys) or group of months (e.g. all May-October periods), the relationship between discharge and the percentage of time that discharge is exceeded. They have general application where the frequency distribution of flows is required for a particular month or group of months which is critical in a hydrological design problem. In addition to assessing the compensation flows needed below reservoirs, they can be used in the licensing of river abstractions and in the determination of sewage effluent dilution - in each case different standards may be applied to different times of the year.

7.2 Variability of calendar month flow duration curves

There can be large differences in monthly flow duration curves between different months for the same catchment and also between different catchments for the same month. The position of the flow duration curve for any month is controlled primarily by the scale of the runoff process, that is, large catchments in an area of high average annual rainfall will obviously have higher daily flows than small catchments in a low rainfall area. This pattern is also apparent when comparing monthly flow duration curves for the same catchment; the wetter winter months will generally have flow duration curves which plot above the drier summer months - this is illustrated in Figure 7.1. Thus the dominant variable controlling the position of any monthly flow duration curve is the average discharge in that month. A second order influence is the effect of geology on the flow regime which results in permeable catchments having flatter flow duration curves (i.e. small variation in mean daily flows) than impermeable catchments. These experience a wide range of daily flows and hence display steeper flow duration curves.

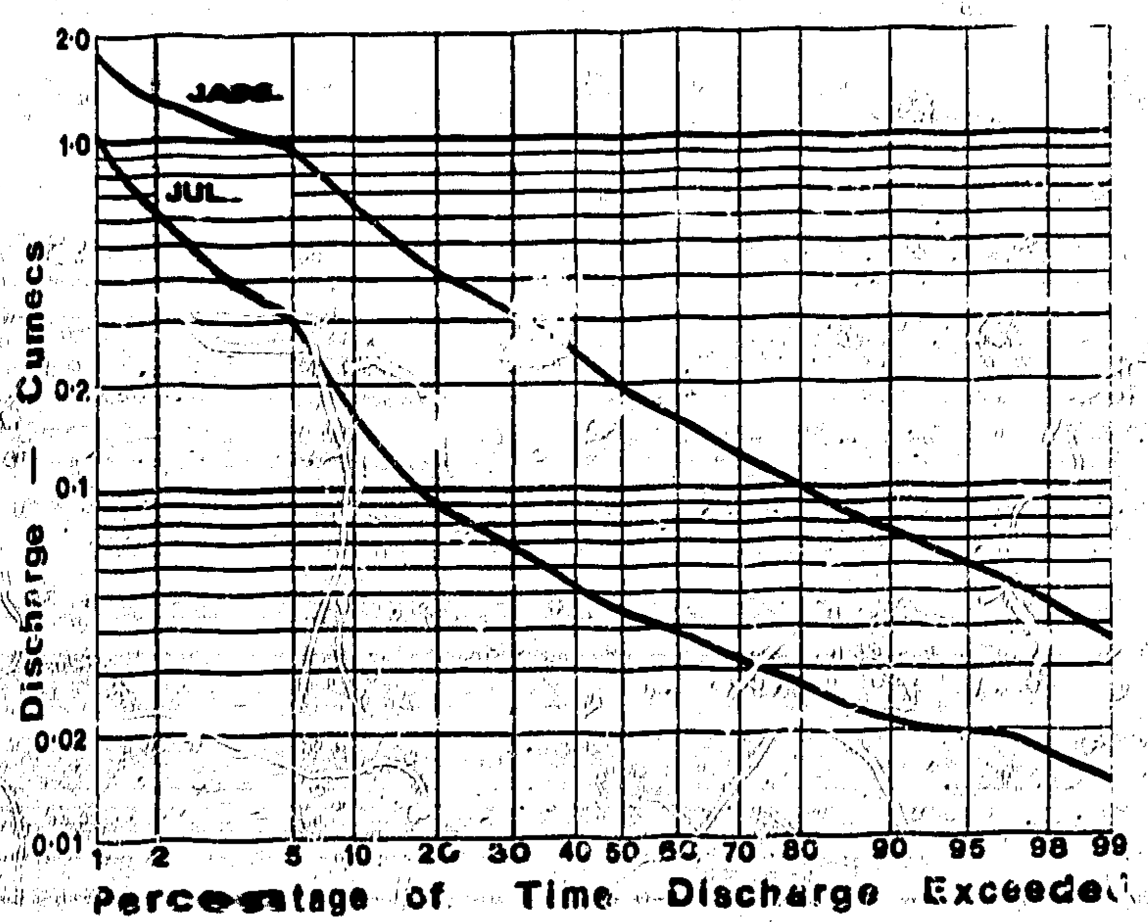

Figure 7.1 January and July monthly flow duration curves for Burbage Brook

7.3 Seasonal flow duration curves

The previous section was concerned with individual calendar month flow duration curves; this section presents seasonal flow duration curves for two or more months and illustrates how they can be used. To avoid any confusion, all references to seasonal curves refer to flow duration curves covering two or more calendar months.

Figure 7.2 illustrates the differences between two six-month curves for the same catchment. The flows during the winter six months are in the main higher than for the summer months and this is reflected in the November-April curve being higher than that for May-October. It can be seen that the long term average flow of 0.17 cumecs is exceeded on 45% of days within the period November-April, but on only 15% of days during the rest of the year. The gradients of the two curves overall are similar indicating that whilst the daily flows over the period May-October are smaller in magnitude, they are just as variable. The two curves on Figure 7.2 have been constructed for six month periods, but seasonal curves can be derived for between two and eleven month periods.

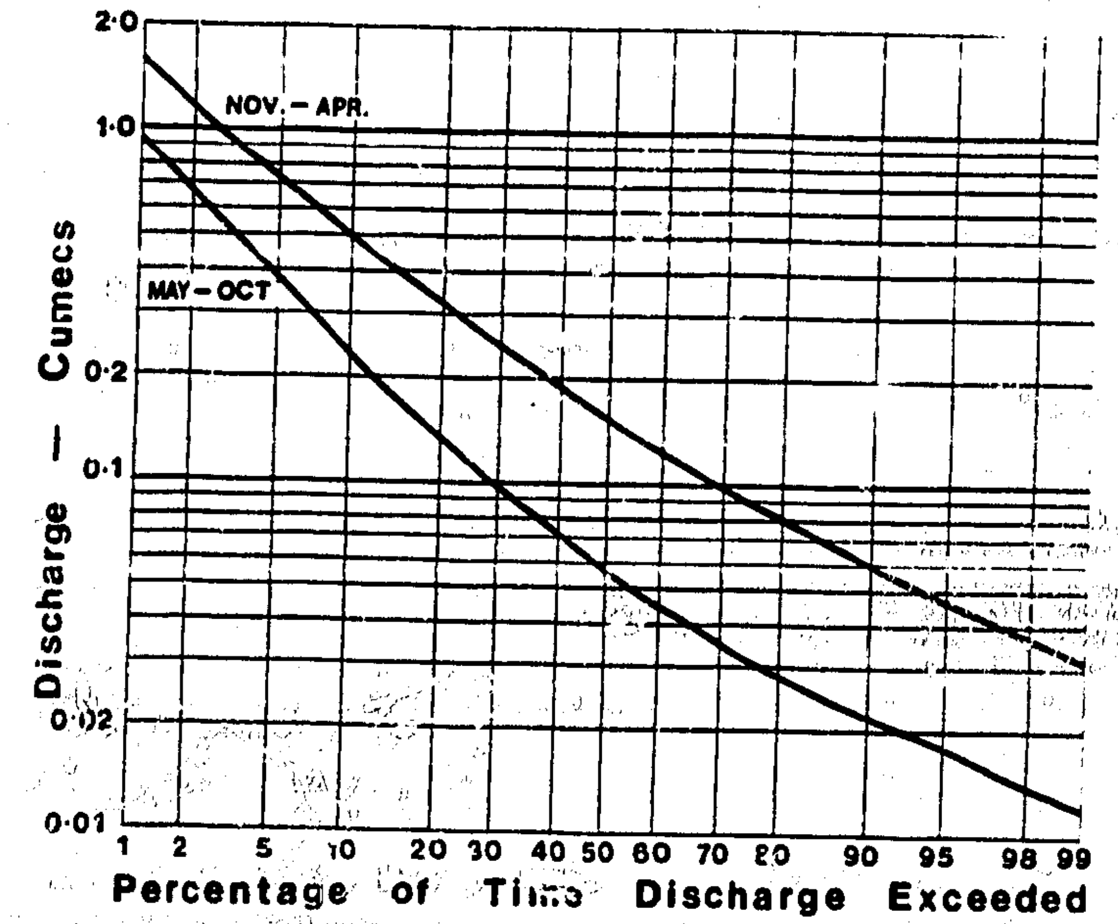

Figure 7.2 Six month seasonal flow duration curves for Burbage Brook

7.4 Flow duration curve estimation manual

Appendix A6 describes how seasonal flow duration curves can be estimated from mean daily flow data. However, for many reservoirs a daily discharge record is not available or it is influenced by the current operating policy of the reservoir. If the natural variability of flows is required then the method described in detail in Appendix A6 for estimation at the ungauged site can be used. The results presented were based on study of over 500 natural flow records. The investigation indicated the variability of monthly flow duration curves both in respect of the gradient and position of the curves could be estimated at the ungauged site from the characteristics of the river basin. The estimation manual presented in Appendix A6 is compatible with other reports in the Low Flow Studies series (Institute of Hydrology, 1980) to which the reader is referred.

8. CONCLUSIONS AND GUIDELINES FOR SETTING COMPENSATION FLOWS

8.1 Legislative background

The historical survey described how the concept of compensation flow evolved from the early 19th century schemes to the present day. The interests of influential industrialists were paramount in determining many of the 19th century awards but other river interests developed and in many cases complicated the problem of determining an acceptable discharge. Present day schemes must consider fisheries, water quality, nature conservation, recreation, and the demands of existing licence holders. There have been several attempts to provide a more structured approach to setting compensation flows. The earliest of these was proposed by Hawksley and this was followed by a series of government committees which met during the inter-war years. Two themes of these enquiries were firstly that many awards had been set at generously high levels and secondly legislation was required to enable awards to be modified without an Act of Parliament. However, these recommendations were not formally introduced until the 1963 Water Resources Act which enabled the then River Authorities in England and Wales to vary a compensation discharge subject to any objection against the proposal being referred to the Secretary of State. Temporary reductions in compensation flow can be obtained by an order under the Drought Act of 1976. Legislation in Scotland, although different from England and Wales, allows similar procedures to be adopted insofar as compensation provision is concerned. The Water (Scotland) Act of 1946 gave power to the Secretary of State to amend compensation water provision which, although inadvertently repealed by the 1967 Water (Scotland) Act, was restored in the 1973 Local Government (Scotland) Act. The Water Act 1958, although no longer applicable in England and Wales, enables temporary reductions in compensation flow to be made in Scotland.

The most recent review of drought legislation (Water Authorities Association, 1985) refers to the possibility of providing Water Authorities with greater discretion in varying compensation flows during extreme droughts. However that review recommends that no amendment to this aspect of the 1976 Drought Act should be sought, since some Authorities have achieved the desired flexibility of operation under existing legislation. Although there are examples where this more flexible approach has been implemented the large number of applications for Drought Orders in the 1984 drought suggests that it has not been widely adopted. The Water Authorities Association also called for improvements to advertising procedures and increased powers to restrict non essential use of water.

8.2 Survey of compensation flows and downstream interests

The conclusions of the historical survey that local precedents, rules of thumb and bargains struck between interested parties had been the basis of many awards was supported by the survey of compensation flows. This highlighted the variety of level and pattern of award between schemes and regions. Most noteworthy is the difference in mean release for the present day between Yorkshire and North West Water Authority areas of 24% ADF and 20% ADF respectively and Northern Ireland of 2.4% ADF. These figures reflect the importance of early industrial interests in the Pennine area, although many of these high awards are still required to maintain adequate effluent dilution. The comparison of releases with river use showed that releases, when expressed as a percentage of the natural flow, were on average 4% higher on industrial rivers than on salmon rivers.

Compensation flows were found to be 35% higher than the natural low flow as indexed by the 95 percentile discharge although for the majority of schemes, flows between the 90 and 5 percentile flow were significantly reduced following impoundment. Recent trends, since 1950, are to set lower awards with none being in excess of 30% ADF. This suggests that many compensation awards are excessive in terms of present day circumstances and that reductions in some awards may bring considerable water supply advantages with negligible environmental effects. The study of spates (in excess of twice the average flow) indicated a reduction after impoundment to on average 30% of that in a natural river. This is of importance for rivers with migratory fish, the largest reductions being downstream of reservoirs with a high net yield.

In the context of the supply function of the reservoir the compensation discharge is equivalent to approximately one fifth of the aggregate gross yield, with a number of individual reservoirs releasing between 20 and 40% of the gross yield. This reflects the influence of Hawksley's rule for setting compensation flows at one third of the gross yield. Any reduction in constant compensation flow may be used to increase the net yield of the reservoir. If the annual volume of release is maintained, but the seasonal distribution is changed, then there will also be an effect on the net yield.

It is of interest to estimate the value of this compensation water when viewed in a narrow water supply context. If there is no demand for additional water in a supply area then there is no demand for this compensation water and the value is limited to any operational savings which may arise from using alternative sources and from any increase in the level of service if restrictions are imposed less frequently. If investment in new water resource schemes is planned then a transfer in use of water from compensation to supply would reduce the cost of any development and the value of compensation water could be estimated from the savings made. These savings will vary from one scheme to another.

Southern Water Authority (1980) have provided an estimate of the economic cost of residual flows made in connection with the Broad Oak Scheme. They estimated that for every 1 Ml/day increase in residual flows there would be a yield loss of 1 Ml/day worth £32,600 per annum at 1979/80 prices or approximately £85,000 per annum at 85/86 prices. (Their figure was based on the unit cost of metered water supply and adopted 60% as the proportion of storage costs). If this figure is applied to the aggregate compensation flow of 1626 Ml/day for the reservoirs considered in this report (Chapter 5) then the value of these releases would be worth £138 million per annum. This figure is presented only to illustrate the cost of the capital investment in providing compensation water, it is <u>not</u> a realistic estimate of the true economic value of current releases. This could only be based on a comprehensive analysis which included the value of downstream river interests. However the impact of compensation flow policy on water supply is of importance and it is interesting to speculate that if the average compensation flows below Northern Ireland reservoirs had been adopted in Great Britain then the existing yield could have been maintained with perhaps one-quarter less storage capacity.

Changes to the yield of existing reservoirs which may result from modifying existing compensation flows must be balanced against any beneficial or detrimental effects on downstream interests. Although the environmental effects of a new reservoir will have a dramatic impact on fluvial geomorphology, water quality and freshwater biology, the effects of modest changes in compensation flow below existing reservoirs will be less significant. The most important changes will arise from differences in the low flow regime of the river and perhaps from temperature and water quality changes if compensation releases are made from different drawoff points. [illegible] immediately below the dam and will reduce

Many downstream interests are discharge dependent and include existing license holders, power generation and dilution of effluents. Others are perhaps level dependent - navigation, recreation and general amenity. Fisheries interests would also be level dependent and sensitive to other flow related variables such as velocity, cross sectional area and wetted perimeter in addition to water quality and river ecology. Chapter 6 discusses the biological aspects of compensation flow policy and the results of studies of the influence of flow regulation on invertebrate populations. Despite the flow requirements for fish being very complex, results are being made available on the flow related preferences for some species including studies of the intragravel stages of salmonids by the Freshwater Biological Association. Although the techniques have yet to be applied in the UK the Incremental Flow Method is now used in much of North America and New Zealand as a water resource planning technique for setting instream flows. The techniques are also currently being developed in Scandinavia.

Although fisheries are often the direct concern, much useful information on the general health of the river can be gained by regular monitoring of the invertebrate population. The invertebrate fauna can be sampled quickly and easily and as it is so diverse it will show a rapid response to a wide range of environmental factors. It may therefore provide a useful indicator of the effect on river biology of modifying compensation releases. A preliminary study of invertebrate faunas below UK reservoirs indicated that there were no detrimental effects of regulation using family level identification.

8.3 <u>Guidelines for reviewing compensation flows</u>

The reservoir owner and operator tends naturally to regard water supply as the primary purpose of a reservoir and compensation releases as a negative aspect of his operation. However, from the point of view of hydrological analysis there is little fundamental difference between water released from storage for purposes of water supply or for purposes of meeting downstream demands. This viewpoint is the basis for proposing a rationalisation of compensation awards. The guidelines outlined below do not represent the policy of the Department of the Environment but are presented as a list of issues that should be considered when setting compensation flows. These are applicable not only to new reservoirs, nowadays an unusual occurrence, but apply with at least equal force when reviewing existing compensation releases.

The guidelines are considered under three headings. The first considers the factors that control the downstream demands. The second relates to technical aids that may be used to quantify the impact of the demands on the flow regime, and to monitor and control releases. The third considers organisational arrangements that would enable maximum use to be made of these technical aids to meet downstream needs in an economical and sensitive fashion.

<u>Downstream demands</u>

The demands on a river that may be made downstream of reservoirs are summarised below. Underpinning this summary is a need for discussion with affected parties to determine their current and foreseen needs and seasonal variation.

1. It is suggested that river interests should be considered upstream of the point where the natural average flow is less than ten times that at the

modifications of compensation flow could result in any major environmental changes downstream of this point.

2. The review of river interests should embrace the following areas:

- Existing licence holders to abstract water for agriculture, industry and water supply
- Dilution of point source effluents, river quality objectives, public health
- Power generation - regard to daily and seasonal demands
- Navigation - maintenance of adequate minimum depth and lockage
- Riparian rights e.g. stock watering and household purposes
- Migratory and coarse fish
- Angling
- Plant and invertebrate ecology - nature conservation
- Amenity - canoeing, swimming, bank side recreation
- Maintaining natural beauty.

3. The survey of the river should identify the location and importance of these interests. A residual flow diagram at average and low flows is helpful in summarising the natural and artificial regime of the river.

4. Existing abstractions should be identified and discussions held with licence holders to assess, and if necessary review, the current need for their licence.

5. Where a new water resource scheme is planned the environmental disadvantages of a zero or very low compensation flow from one or more existing reservoirs may be less than that of a new scheme involving reservoir construction. The impact of setting zero compensation flows should be assessed. This reflects the large weight that is given nowadays to the environmental disadvantages of new impoundments.

6. The distinction must be clearly made between the downstream needs for discharge and levels. For example many amenity interests are 'level sensitive' and their needs can be met by very low discharges with water levels maintained by weirs.

7. It is important that future trends in river interests and supply are taken into account.

Technical aspects

Even if downstream demands on river flow had not altered, a review of compensation releases would be timely because of technical advances. These are summarised below and relate to hydrological and biological sciences which can be used to define much more closely the natural flow regime and assist in determining the water requirements for many of the downstream demands. In addition, improvements in the monitoring and forecasting of flow have resulted from technical advances in the field of instrumentation and control, leading to greater efficiency in the operation of water resource systems.

1. The assessment of compensation flows should be based on a detailed survey of downstream requirements. However, for small reservoirs on short tributary streams, detailed surveys may not be justified and, in the absence of any significant river interests, the 95 percentile or mean annual 7 or 10 day minimum discharge could be adopted. The basis for this is that the natural low flow discharge would be maintained. This would be

precedents. If implemented this would lead to a reduction in compensation flows by approximately 25% at the reservoirs studied. The seasonal variation in flow duration curves could be used as the basis of a varying flow policy e.g. use of the 95 percentile calendar month flow.

2. Where river interests can be evaluated then comparisons between different schemes can be made by considering the nature and importance of the interest and, where appropriate, by weighting the interest according to the length of river reach which is influenced by the reservoir releases.

3. Routine water quality surveys should be implemented to provide data for use in an appropriate water quality model where point source pollution needs to be considered. The influence of changes in compensation flows on downstream quality should be examined in the light of existing quality objectives.

4. Where a migratory fishing interest is influenced by compensation flows, then a fishery survey should assess its commercial and sporting value and the time of year at which salmon and trout spawn, eggs hatch and upstream and downstream migration occurs. The important physical, chemical and biological factors for maintaining the ecology of the river should be estimated. Angling activity should be determined and the local importance of a particular fishery identified.

5. The change in discharge regime should be simulated for different release policies and displayed as hydrographs and summarised as flow duration curves. Representative reaches should be selected by fisheries staff, hydrometric surveys should be carried out and discharge simulations converted to depth, velocity, cross sectional area and wetted perimeter. These physical characteristics of the discharge regime over critical reaches e.g. spawning grounds should then be related to the published information on the optimum requirements for fish. Photographs of a range of river reaches in different flow conditions should be taken to illustrate site specific conditions at given discharge rates. Where possible the effects of water quality and temperature changes should be assessed.

6. Fish population surveys by electrofishing and using catch statistics should be carried out and where available, migratory fish movement should be determined using fish counters. If changes in compensation flows are made then these surveys can be repeated to monitor the fisheries impact.

7. These hydrological and biological surveys should be used to determine the flow requirements for fish in preference to using fixed percentages of the average flow. The adoption of seasonally varying compensation flows should be considered in these studies. This is facilitated by the techniques developed for enabling seasonal flow duration curves to be estimates at ungauged sites. For example if the months and approximate range of discharge for migration can be established then the number of days in this flow range can be preserved for the critical months.

8. Block grant allowances have been used primarily for freshet releases during specified months of the year, and a secondary volume kept in storage for release in emergency situations e.g. a pollution incident or a drought. Use of a block grant is thus recommended, primarily as it gives additional flexibility of operation, which is important when the flow requirements of fish are not known precisely. Emergency provision may also allow for changes during the review period.

9. There is little firm evidence that freshets aid salmon migration, however they may act to 'freshen up' the river and continue to be supported by a number of organisations particularly in Scotland. However, the release should be controlled by fishery requirements and the specification of a given frequency or day of release in a licence mitigates against this. There is a clear need to evaluate the effectiveness of artificial freshets for ameliorating the environmental impact of reservoir impoundment.

10. Where appropriate, requirements for coarse fisheries should also be based on water quality, biological and hydrological surveys.

11. It is not possible to generalise the flow regimes needed for fisheries requirements although the national collation of fish count and hydrometric data may enable simple empirical relationships to be developed. These would only be of value for preliminary estimates and would need to be followed by a fishery survey carried out and assessed by an experienced fisheries biologist.

12. Invertebrate sampling before, and at regular intervals after, any change in compensation flow will provide an indicator of any beneficial or adverse ecological change.

13. The release of a constant compensation flow is intrinsically wasteful and seasonally varying compensation flows will generally be more beneficial to water quality and fisheries interests. For example, high compensation flows for two or three months of the year balanced by lower discharges for the remainder of the year may lead to improvements in water quality or river ecology without any loss of net yield.

14. Unless the release and demand pattern is particularly simple the water supply implications of any change in compensation flow should be evaluated using reservoir simulation techniques. The most critical case is the decrease in net yield with summer maximum releases particularly on reservoirs with relatively small storage capacities.

15. Operational difficulties associated with making very variable releases are stressed by some Authorities although the advances in instrumentation and control should make flexible releases a practical proposition.

16. When appraising the water requirements downstream of the dam it is important to note that the total requirement is not the sum of the individual needs. In most situations one river interest will be critical and if met, the requirements of other interests will also be satisfied.

Organisational aspects

Although legislative procedures enable compensation flows to be modified, the opportunity to make full use of the integrated nature of modern water resources systems and recent technical advances have been taken up by few organisations. Changes in compensation releases are seldom viewed as a means of increasing reservoir yield, operational flexibility or for improving flow conditions to the advantages of downstream river interests. We would support the development of a more flexible response to compensation flow provision to be developed within the framework of existing legislation. A central feature of the following recommendations is that compensation flows should be periodically reviewed.

1. When water resource developments or the operating policy of a reservoir are being examined then the existing compensation flows should not be

of particular importance when an environmental impact study of compensation flows has not been previously carried out i.e. for the majority of UK reservoirs.

2. The objective of such a review should not be restricted solely to improving the yield of the reservoir but should include improvements in water quality, fisheries and general amenity; in other words those same issues as were relevant at the time of the initial compensation decision plus any other factors whose importance has increased thereafter.

3. It is not possible or desirable to propose national standards for setting compensation flow. The requirements of the river below the dam will always be site specific and hence the compensation flow should vary from one location to another.

4. In the same way that these requirements vary from one location to another they will also vary in time. It is proposed that periodic reviews of compensation provisions are carried out at intervals of approximately 10 years where there are known to be significant changes in reservoir demand or downstream interests. This will also provide an opportunity to consider the results of any changes in compensation flow.

5. The value of any changes in net yield must be balanced against the value of competing downstream water uses, including financial and intangible aspects. This balance must be established after discussion with interested parties and the consideration of a range of different strategies which may include, for example, improvements to effluent discharge as a method of enabling compensation flows to be reduced.

6. Compensation flows should be set some distance below the dam and releases used only to maintain the discharge at this point. The location of this maintained flow point should be determined by the river interests e.g. fisheries, dilution of effluent, amenity.

7. Current delays associated with the advertising arrangements for Drought Orders should be removed.

8. Clearly defined control rules could replace 'Drought Orders' for reducing compensation flow in times of extreme drought. Water supply interests could be safeguarded by having reductions in compensation flow linked to time of the year and level of storage. River interests could be safeguarded by requiring any reduction in compensation flow to be linked to a restriction on the consumer, e.g. a ban on non essential use of water would have to come into effect when a given reduced level of compensation flow was released.

9. Current legislation in England and Wales has been used by Yorkshire Water Authority and others to revise compensation flows by expressing the licence in terms of control rules based on reservoir storage and month of year. This provides a mechanism for more flexible reservoir operation and may reduce the need or frequency of application for a Drought Order in respect of compensation flows.

10. Any compensation flow arrangements must be clearly defined and understood both by the general public and reservoir operators.

11. It is recommended that a report is made available of the issues which were considered and the principles that underlie any revision. This is particularly important for Regional Water Authorities where the 'supply' and 'river' interests are not so openly represented as they are in the

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APPENDIX A1 HISTORICAL DEVELOPMENT OF SETTING COMPENSATION FLOWS

1.1 Introduction

An essential background to the study of existing compensation flows is an historical appraisal of how the concept of compensation water was first perceived and introduced to reservoir management, and how it has subsequently developed. Prior to 1945, evidence from interested parties on a proposed reservoir scheme had to be formally presented to Parliament in the form of a Private and Local Bill. This resulted in much documentative evidence being available. This account deals primarily with this period and shows, by reference to a wide variety of agreements reached over levels and methods of compensation discharge in UK, how precedents for setting compensation flows were established, and subsequently applied to schemes in other areas. The search for a coherent approach to assessing compensation flows is examined and detailed examples presented from major water resource schemes (Section 1.4). Scotland does not have the same legislative procedures as England and Wales, and consequently different precedents were developed for Scottish reservoirs. For this reason a detailed account is presented of the development of one major Scottish water resource scheme to supply Edinburgh (1890 to present day), since this established several important precedents (Section 1.6). A select chronology of events is presented in Table A1.1, which summarises significant legislation with respect to compensation provision.

1.1.1 Documentation

The construction of impounding schemes is comparatively well-documented, compared with many other types of large-scale development. In addition to the relevant books and articles found in libraries, and the documentation to be sought in the archives and offices of the relevant water undertakers and other bodies with an interest in the watercourses, a great deal of information may be obtained in the printed and manuscript records of Parliament and the appropriate government departments.

Bills submitted to Parliament were scrutinised by one House and then the other and, if it was rejected by either, it fell automatically in both. The proposals contained in the Bill might prove so contentious that a debate might be initiated on an amending motion, or even at the second or third readings, and the proceedings be published in Hansard. More usually, everything hinged on the attitude of the Select Committees appointed separately by both Houses to scrutinise the measure after it had been given a second reading 'on the nod'. Where the Bill was opposed, a record of the Committee's minutes of evidence can now be consulted in the House of Lords Record Office. After 1899, it was the practice for most Scottish schemes to be promoted in the form of a Provisional Order. Where opposed, the Secretary of State was required to hold an inquiry before four (Scottish) Commissioners, two drawn from the House of Lords and two from the Commons. Their minutes of evidence may be studied in the Scottish Record Office.

Except for a comparatively few precedents of policy laid down for Water Bills, the impartial and non-expert members of the committees had to decide the fate of the schemes entirely on the merits of the arguments put forward on behalf of the promoters and opponents of the Bill by legal counsel, and supported by policy and expert witnesses. Engineers were very prominent among the latter. It was customary for both Houses of Parliament, and in the case of Scotland the Secretary of State, to accept without further discussion their respective committee's findings as to whether the scheme should be approved. There was little continuity in the membership of committees, or any scope for independent inquiry and research. The Royal Sanitary Commission of 1869-71 was only one of a long succession of bodies to describe and criticise this ad hoc way of appraising schemes (Royal Sanitary Commission 1871).

1.2. The origins and early application of the concept of compensation water

The first priority of a water undertaker was to establish a right to abstract water. For this an Act was required and, during the late eighteenth and early nineteenth centuries, the Acts authorising the construction of canals had to specify which streams were to be tapped, and how the other stream users were to be protected from injury (Hadfield 1959). Water undertakers had to follow a similar procedure. Under the Waterworks Clauses Act, a consolidating measure of 1847 (10 Victoria, cap. 17), water undertakers were expected to pay full compensation to anyone injuriously affected by the diversion of stream water and construction of waterworks.

1.2.1 Different forms of compensation

Restrictions on abstraction

The comparatively weak bargaining position of many water undertakers was illustrated by an Act of 1830 (11 George IV cap.IV) which authorized Sheffield Water Company to impound the Wyming Brook, which flowed into the river Rivelin, and thence into the rivers Loxley and Don. In order to protect the mills, forges and other interests downstream, which were 'worked or put in motion or supplied by the waters', the water company was prohibited from abstracting water, except in 'times when the said waters shall be abundant and more than sufficient for the purposes to which they are so applied'. Two referees were to be appointed, one by the industrial interests and the other by the company, to 'determine what shall be deemed the flood or spate or surplus water' that could be abstracted without injury to the mills, and to prescribe where and how the gauges to measure the flood should be fixed. A third engineer or umpire would be appointed in the event of dispute; the water company would meet the cost of maintaining the gauges.

Single purpose compensation reservoirs

Sheffield Water Company later took the 1830 Act further and sought powers to establish a permanent surplus of water by artificial means. A further Act of 1845 (8 & 9 Victoria, cap. clxxv) conferred powers to build 2 reservoirs 'for storing up water for the owners, lessees and occupiers of mills and other works' on the river Rivelin, and on the river Loxley below its junction with the river Rivelin, as a 'compensation to them for the whole of the waters' of the Wyming Brook, which would thenceforth be used for supply purposes. The company undertook to construct and maintain the reservoirs, and a keeper would be employed, who would discharge the water under the direction of a committee of millowners, whose terms of reference were laid down by the Act.

Further attempts were made to find new sources of water for Sheffield, and to reduce the restriction imposed on the quantities and timing of existing supplies (Swales 1932). Under an Act of 1867 (30 Victoria, cap. xcvii), a compensation reservoir was to be built at Damflask, capable of [illegible] gallons per minute. Once in use, the water from all

the existing reservoirs in the Loxley valley (Strines, Agden and Dale Dyke) could be used for supply purposes, subject to the payment of financial compensation to any mill or works that had sustained injury as a result of the change. The Damflask reservoir was completed in 1896.

Dual purpose compensation and supply reservoirs

The opposition to schemes often provided the stimulus, and at times the necessity, for introducing alternative forms of compensation. This is demonstrated by the protracted attempt of Manchester undertakers to exploit the Longdendale Valley, during the 1840s. The original intention of the engineer, La Trobe Bateman, was to construct a reservoir exclusively for the millowners and, under an Act of 1847 (10 & 11 Victoria, cap. ccii), the Corporation was required to build 'a compensation reservoir'.

Having made this much progress, Bateman changed his mind, and devised a greatly enhanced scheme for the virtual control of all the gathering grounds in Longdendale. Under a further Act of 1848 (11 & 12 Victoria, cap. ci), the same reservoirs were to provide both supply and compensation water. The Corporation would release at least 75 cubic feet of water per second in a manner to be decided by a majority of the millowners.

Monetary payments

The discharge of compensation water from compensation or dual-purpose reservoirs became the usual method of awarding recompense to injured parties, despite the fact that the Waterworks Clauses Act of 1847 made explicit provision for only pecuniary compensation. Especially on highly industrialised streams, the difficulties of negotiating separately with each claimant for damages, and the cost of satisfying him, would have made abstraction impractical. Undertakers argued that it would be far more convenient both for themselves and other water users if compensation was given instead in the form of water, released in a regulated manner (Constable et al. 1900). There were many instances where millowners had themselves built reservoirs in order to secure a more adequate and even flow in summer.

In practice, monetary compensation was normally used only to retrieve situations where arrangements for compensation water proved unexpectedly inadequate. Such an occasion arose when Manchester Corporation discovered that rainfall in the Longdendale valley was a twelfth less than expected. A choice had to be made between a further impounding scheme or a reduction in compensation flow. In 1854, the Corporation took the cheaper course of obtaining an amending Waterworks Act (17 Victoria, cap. xxxviii), which permitted a reduction by agreement of the discharge from two-fifths to a third of the available yield. All parties agreed that the flow far exceeded what could be 'usefully employed' by industry (House of Lords Record Office (HLRO), Commons Select Committee, minutes of evidence). The Corporation subsequently purchased from the millowners a third of the original compensation water - the maximum permitted by the Select Committee (Bateman 1884).

It was through these various ad hoc attempts to gain access to an increasing number of streams that the concept of compensation flow emerged as an integral part of impounding schemes. The precise manner in which the water was given reflected the nature of the stream and its valley, the previous experience of the undertaker, the preoccupations and relative strength of other water users, and the precedents laid down by Parliament. The Bill promoted by the Bradford Corporation in 1854 (17 & 18 Victoria, cap. cxxiv) may be cited as an example of the different forms in which compensation could be given, even within one undertaking. The Corporation proposed to abstract water from the Wharfe, Aire and Hewenden valleys, and construct a compensation reservoir in each (James 1866). The experience of other undertakers indicated that Parliament would expect a third of the available yield to be set aside for compensation purposes (HLRO, Commons Select Committee, minutes of evidence, vols 2 & 3; Lords Select Committee, minutes of evidence, vol 5).

The industrial interests of the three river basins adopted different approaches in safeguarding their supplies. So as to ensure that the storage capacity of the reservoir on the Wharfe provided adequate compensation, an eminent civil engineer, Sir William Cubitt, was to be appointed to decide its dimensions. In the event of his finding it impossible to give adequate compensation within the limits set by the Act, the area to be appropriated for supply purposes would be reduced by a commensurate amount. In the Aire valley, millowners and dyeworks avoided such problems by securing a guaranteed flow of 1.35 million gallons a day (mgd) from the reservoir. If this amount was not provided, the Corporation would make payments 'by way of liquidated damages and not of Penalty'. Those in the Hewenden valley adopted a third course. If, at any time within six years of the waterworks being built, the amount of compensation water was less than the average supply previously enjoyed, the Corporation would make a once-and-for-all payment in compensation.

1.2.2 Opposition from vested interests

Parliamentary committees spent more time considering the issue of compensation than any other aspect of reservoir development. Much of the controversy reflected a basic lack of appreciation of the different uses made of stream water, and the importance attached to each in the changing economic and social circumstances of the river basins and beyond. Most of the early reservoir development occurred in areas where the growth of industrial towns had resulted in a burgeoning demand for water, and where 'every available foot of fall in the larger rivers had been utilised' by millowners (Paterson 1898). As well as driving machinery, water fulfilled a number of other industrial uses, particularly in the paper-making and textile industries.

The primacy of the industrial interests in seeking compensation for the effects of impounding schemes was most clearly recognised by a Standing Order introduced in both Houses of Parliament in 1862, whereby those promoting Bills to abstract water had to give notice to those with mills or factories up to 20 miles downstream (as measured along the stream) or, if shorter, to the confluence with a navigable river (Williams 1949). No reference was made to other potentially affected parties.

Masters of the situation, millowners were able to establish a precedent whereby compensation water was discharged in an intermittent, rather than a continuous, flow so as to provide a greater volume of water during the working hours of the mills. The impact of such irregularity on the stream courses was highlighted by Lord Savile, the largest landowner in the Calder valley of the West Riding when, in 1887, he learned that the Halifax Corporation, following representations from millowners, intended to follow the normal practice of providing a discharge of 12 hours a day, 6 days a week. If unamended, the Bill was likely to turn the much visited beauty spot of Hardcastle Crags into an unsightly ditch on Sundays. Despite protests from millowners, a Select Committee of the House of Lords set the precedent of substituting a continuous for an intermittent flow (Act 1888, 51 & 52 Victoria, cap. xliv).

In his polemic, Compensation discharge in the rivers and streams of the West Riding, Paterson (1898) contended that the time had come for the water power interests to recognise and accommodate the needs of other users. Not only was the role of water power being displaced by steam power and electricity, but the role of the rivers in removing sewage and trade effluent had become increasingly crucial. In the West Riding, where he calculated that three human beings occupied every two acres of land, river water had a particularly vital role to play in the well-being of the community. There was, however, little chance of redress until a single authority was appointed with both the responsibility and resources to safeguard this aspect of public health. It was in this context that the creation of the West Riding County Council, under the Local Government Act of 1888, was so important for river conservation. Under the Act, county councils were set up for each part of the country, with the powers inter alia of a sanitary authority. Because of their size and strength in terms of rateable income, and the fact that they had no direct responsibility for water supply and sewerage, they were uniquely placed to take a more independent view of river management. Having been alerted to Lord Savile's initiative, and having co-operated with him in persuading the town of Morley to adopt the principle of continuous flow in a Bill to impound a further tributary of the Calder, the County Council was 'brought face to face with this hitherto obscure branch of river conservancy' (Paterson 1898).

The County Council urged Parliament to make a Standing Order, instructing Select Committees to insist on the provision of a continuous flow of compensation water, wherever possible. Meanwhile, the Bradford Corporation had promoted a Bill to exploit the Nidd valley. Although the water power interests prevailed in the first House, the Commons Select Committee granted 'a regular, equal and continuous flow', after hearing only four witnesses of the County Council (Act 1890, 53 & 54 Victoria, cap. ccxxxi; HLRO, Commons Select Committee, minutes of evidence, vol 6). At the Committee's instigation, a Standing Order was introduced, whereby every committee considering a Water Bill had 'to enquire into the expediency of making provision so far as may be practicable, that the whole or minimum amount of compensation water would be discharged daily in a continuous flow' (Williams 1949).

Despite this success, the views of the County Council, and of the West Riding of Yorkshire Rivers Board (which was set up under the Council's aegis), did not always prevail before Select Committees, particularly on such issues as the right to inspect gauges and sue for penalties. Millowners objected to the encroachment on what had been previously their prerogative, and water undertakers, most of whom were borough corporations, resented the intervention of the County Council, and protested at the imputation that they could not be trusted to comply with their statutory obligations.

There remained the 'deep-rooted conviction that a stream exists only for millowners'. In some cases, not even the majority of millowners benefitted. The agent of Lord Savile told the Commons Select Committee on the Bradford Corporation Water Bill in 1890 how it often happened that only 'two or three active men' attended a committee of management; they settled the day of meeting, and decided how the water should be released, irrespective of how this would correspond with the working hours of mills further downstream. Other millowners were 'not aware of what had been done, and although they were suffering they were not aware of the cause of their suffering'. The Select Committee tried to guard against this danger in the Nidd valley by including not only all the millowners on the committee of management for the Gouthwaite compensation reservoir, but also three riparian proprietors appointed by the County Council. Unfortunately, the Select Committee made no provision for any widening of the membership at a later date, or for enabling industrialists to resign once their mills had ceased to use the river. Because the millowners' voting rights were based on the amount of foot-fall of water to the mill-tail race, they soon came to reflect the potential, rather than the actual, use of water power on the river (Smith 1964 & 1965).

Whilst Parliament took account of changing circumstances during its consideration of Bills, everything had to be 'cut and dried' in the eventual Acts so as to minimise any doubt and ambiguity in adjudicating between the contending parties thereafter. The clauses were so tightly drawn that the only way of bringing the provisions of an Act into line with changing demands and practices was to incur the cost and difficulties of promoting fresh legislation. This measure proved a major deterrent to the reform of compensation practices.

1.3 The assessment and reappraisal of compensation flow

1.3.1 The search for a formula

It was one thing to decide that compensation water should be given, and another to decide how much. The need to assess the amount carefully was underlined by Thomas Hawkesley in 1884, when he warned of how it could cost up to £140,000 in capital outlay to provide 1 mgd of compensation water (Rennison 1979). Water undertakers argued that it was enough to provide the same amount of water as would have flowed in dry periods. No-one would suffer because millowners had previously adjusted their machinery to this minimum flow in order to make sure it could be used throughout the year. Millowners denied this by claiming that their streams were exceptional in having a much more even flow, or that they had installed balancing reservoirs or auxilliary steam power to ensure that the machinery could be used in both drought and flood. In view of the time and cost of deciding these major points of issue, it was in everyone's interest to find a formula for fixing compensation levels that could be applied universally.

In doing so, account had to be taken not only of usage, but also of the available yield of the catchment. Whilst the construction of canals had represented in many parts 'the first systematized attempt to render all the water of a district available for useful purposes', the canal companies had, in practice, collected very few data on the rainfall and none on stream-flow over long periods of time. As Bateman (1884) recalled, 'a rain gauge, except in the hands of a philosophical observer, was a thing unknown'. Because of the need to promote schemes hurriedly in order to meet the pressing needs of share-holders and consumers, and often to pre-empt a rival undertaker, there was no scope for making systematic measurements over several years.

1.3.2 The Hawksley approach

Before the Royal Commission on Water Supplies in 1868, Thomas Hawksley argued that it was only economical to impound the average run-off as represented by the three driest consecutive years on record. In the absence of stream-flow records, he suggested that the amount could be estimated from rainfall data on the assumption that only 80% of the average rainfall fell on such occasions. From this estimate, the equivalent of 14 or 15 inches should be deducted to allow for evaporation and percolation. The resulting figure, called the available rainfall or reliable yield, could then be expressed in terms of gallons of water per day for the drainage area in question. He offered no data in his evidence to support these assumptions.

Experience in the Pennine catchments indicated that the equivalent of 8 to 10 inches of rainfall was sufficient for industrial purposes. This represented a third of the reliable yield as calculated on the basis of Hawksley's formula (Prescot Hill 1931). The Rivington scheme of Liverpool Corporation was reputed to be the first to allocate one third to compensation, and two-thirds to supply purposes. Because most of the early schemes were promoted in the Pennines, there were many instances of the same ratio being applied. It held out 'the prospect of abundant supply to the towns without injuring existing interests' (Law 1956). Unless there was 'something special in the circumstances of the Mills', engineers regarded the ratio as a fair and liberal compensation.

The rule of a third for compensation water (and a quarter where no industry was present) was, however, only 'a centre point on which you might turn rather widely'. Thomas Hawksley told a Select Committee in 1854 that the release of a third would be 'more than ample in hilly and mountainous districts of hard character and surface', where three-quarters of the natural flow had previously been lost for all practical purposes in the form of floods.

The proportion of water set aside for compensation purposes might have to take account not only of natural flow characteristics, but also of the greater variety of uses made of water in some parts of the country. During the promotion of a scheme to impound Loch Katrine, 35 miles from Glasgow, it was soon discovered in 1854 that much greater account would have to be taken of the navigation interests when deciding the level of compensation flow (Glasgow Corporation 1936). On behalf of the Forth Navigation Commissioners, the Admiralty successfully opposed the Bill, on the grounds that the navigation of the Forth would be seriously affected by the loss of water in the river Teith (Bald 1853; Bell & Paton 1896). Under a further Bill of 1855 (18 & 19 Victoria, cap. cxviii), it was agreed that the Corporation should abstract up to 50 mgd from Loch Katrine for supply purposes if 40.5 mgd were provided from 'the compensation reservoir' of Loch Venacher, which would be adapted for that purpose. The Corporation paid £7,000 in compensation 'for any injury which the navigation of the River Forth could sustain', and a further £4,500 when the capacity of the waterworks was doubled under an Act of 1885 (48 & 49 Victoria, cap. cxxxvi).

1.3.3 Revising yields and compensation awards

By the inter-war years, a great deal of attention was given to revising the bargains struck in earlier Acts. Water undertakers stressed how even a small reduction in compensation could contribute significantly to the cost effectiveness of schemes, either through increasing supplies or by reducing the size of the reservoirs needed. According to one calculation, a reduction in flow from a third to a fifth of reliable yield could lead to a difference of 40% in storage requirements (Blackburn 1936). Ways had to be found of mitigating the obligations of the past, without causing undue injury to any other parties in the future (Prescot Hill 1931).

There was nothing new in the concept of amending legislation. Many undertakers embarked on schemes without recognising the cost and time required in constructing and maintaining the reservoirs and associated works. The reason for amending legislation was often a failure to estimate the reliable yield of the catchment correctly. Bateman recalled (HLRO, Commons Select Committee, 1978, vol.21) how 'all of us are wiser than we were 30 years ago - at that time waterworks were very much in their infancy and we knew very little of what could be collected and we made the best calculations we could'.

By the turn of the century, many undertakers and their consulting engineers attacked the illogicality of estimating reliable yields on the basis of rainfall, rather than river flow. According to W J E Binnie (1922) 'rainfall has nothing to do with the minimum flow of the river, provided the rainfall is above a certain amount' (Holme Lewis 1921). Much depended on the natural storage properties of the underlying rock. The dry weather flow was likely to be high where there was ample ground storage, but low where impermeable rock was exposed, or fissures conveyed the water quickly away from the watershed. The slope and extent of the catchment, vegetation and the presence of artifical land drainage systems had also to be taken into account.

At a meeting of the Institution of Civil Engineers in 1912, a contributor drew on American experience in emphasising the value of gauging stream flow (Mansergh & Mansergh 1912), and Binnie (1922), in a presidential address to the Institution of Water Engineers, argued that this was the only accurate way of assessing the need for compensation water. According to Binnie, the Durham County Water Board Act of 1922 (12 & 13 George V, cap. xxiii) was the first to be based wholly on this principle, and on the fact that compensation water was of no value to anyone when the river already exceeded a certain flow. As full compensation, the Board was required to discharge 2 mgd as measured within 300 yards of the Burnhope reservoir. On the premise that it was irrelevant to downstream interests how much water was released, so long as a statutory minimum flow was maintained 2 or 3 miles downstream, where the water was required for industrial and other uses, the Act authorised a reduction in compensation flow to a minimum of 400 000 gd whenever the river level reached a point on a gauge that indicated it was not 'materially affected' by the reduction. The position of that point on the gauge was to be agreed by the Board, the Wear Fishery Board, and the local authorities, or, in the event of dispute, by the Ministry of Agriculture and Fisheries.

The value of reappraising the basis for calculating compensation flow was illustrated by the Birkenhead Corporation. When the Corporation promoted an Act of 1907 (7 Edward VII, ch. cxxxi) to impound the rivers Alwen and Brenig in Denbighshire, the Parliamentary Select Committees insisted that a third of the reliable yield should be allocated for compensation, as calculated on the basis of rainfall. According to Binnie (1922), the Corporation's consulting engineer, it proved 'a waste of public money without benefit to anybody'. Gauge readings of stream flow over the subsequent 12 years indicated that the amount set aside represented 8 times the average natural flow of the stream at the site of the Alwen dam during the driest month recorded, and twice the average flow of the driest month of an average year. If compensation had been based on the actual dry weather flow of the Alwen, Parliament would have realised that 1.8 mgd, rather than 3.6 mgd, would have sufficed. Not only would a lower level of compensation water have reduced the burden on ratepayers, but it would have postponed the day by up to 20 years when Birkenhead would have to find a further source of supply for its increasing population.

In his presidential address of 1922, Binnie argued that, because of the length of time taken to construct a reservoir, Parliamentary committees should stipulate that compensation water should not be less than natural flow in the driest month recorded by gauges during the period that elapsed between the promotion and completion of the scheme. In the case of Birkenhead, an amending Act of 1929 (19 & 20 George V, ch. xxxvi) reduced compensation flow to an average of 2.25 mgd, whereby 3.0 mgd would be released in the months April to September, and 1.5 mgd from October to March (Public Record Office, HLG 54, 190; Baker 1934).

Many undertakers, particularly in highly industrialised valleys, failed to secure even this measure of redress and compromise. Whilst the principle of continuous flow was generally adopted in the case of new schemes from the 1890s onwards, intermittent flow continued from those already built. When the town of Keighley promoted a Bill in 1898 (61 & 62 Victoria, cap. cclv), Parliament upheld the practice of intermittent flow on the basis that it had been previously permitted on the watercourses under Acts of 1869 and 1891 (Law 1956). As Holme Lewis (1921) complained, Parliamentary committees were reluctant to depart from precedents established when 'there was not the same need ..... to study the economics of the water resources of the country'. They turned a deaf ear to the pleas of undertakers that millowners should put their mills on a more efficient footing so as 'to do their work with a smaller quantity of water'.

The reluctance to adjust the basis of earlier schemes meant that the pioneers of reservoir development suffered most. One of the first schemes of its kind was the Belmont reservoir which, by an Act of 1824 (5 George IV, cap. cxxx), was constructed for the millowners in compensation for the appropriation of the Daddy Meadow Spring for 'the inhabitants of Bolton'. When a rise in demand made it necessary to exploit further grounds, and to build the Dingle reservoir, the water company agreed, under an Act of 1843 (6 & 7 Victoria, cap. lxxiv), to raise the embankment of the Belmont reservoir. This had the effect of providing 2.25 times the average daily supply to Bolton (Swales 1926), which was soon regarded as being far too generous in the light of what proved to be the actual yield of the catchment and the rising demand for water. The millowners nevertheless insisted that they needed all the compensation water available in order to keep abreast of industrial demand. Thus the prospects of Parliament agreeing to any significant change were bleak.

1.3.4 Alternative sources of compensation water

Bolton Corporation therefore had to resort to a variety of devices to increase the quality and quantity of water available for supply purposes. When there was no prospect of Parliament agreeing to any significant reduction, a variety of other devices was used to improve the quantity and quality of water available for supply purposes. In order to bring its waterworks into line with the more usual practice of abstracting compensation water from the lower and more polluted parts of a watercourse, Bolton Corporation promoted a Bill in 1905 to convert the Belmont reservoir to supply purposes, and to substitute compensation water from the Delph, Eagley and Hordern reservoirs to be built lower down the valley. The strong opposition to the proposals caused the Parliamentary committees to compromise by allowing only part of 'the Belmont water' to be diverted, and only a third of the Delph water to be used for compensation purposes (Act 1905, 5 Edward VII, ch. cciv).

The Corporation promoted a further Bill in 1922 to construct five wells. Because of the chemical properties of the water from the Eagley well, the Corporation proposed substituting it for half the compensation water from the Delph reservoir. The principal dyeworks downstream objected on the grounds that the mill had been established on the assumption that the earlier agreements embodied in the Acts would be upheld. Whilst the Corporation was not seeking to reduce the quantity of compensation water, the higher levels of sodium carbonate would be deleterious to dyeing operations. Again, the Parliamentary committees compromised: the Corporation was empowered to substitute the well water for Delph water, but only in the ratio of 2 : 1 (HLRO, Commons Select Committee 1922, minutes of evidence; Act 1922, 12 & 13 George V, ch. xciii). The Corporation was still obliged to release 3.4 mgd for compensation purposes, compared with 1.1 mgd available for town supply (Swales 1926).

Sheffield Corporation also resorted to considerable ingenuity in meeting a shortfall in supplies. The upper tracts of the river Don were set aside for supply purposes, and the existing works adapted to use the lower, polluted reaches for compensation (Hawson 1968). A Bill was promoted in 1919 to abstract up to 10 mgd from a point near the Blackburn sewage works, 1 mile below the city boundary, and to pump it to a balancing tank 11 miles upstream and immediately below the Damflask (compensation) reservoir (Figure A1.1). The treated water would then be discharged into the river as compensation water.

While the Parliamentary Select Committees accepted the urgent need of Sheffield for more water, and approved the novel proposal in principle, constraints were imposed. The maximum quantity to be abstracted, restored and used as compensation water was limited to half the statutory amount of water required. The treated water was to contain at least an equal quantity of reservoir water, subject to an additional 10% of treated water. Standards of purity were imposed. The trial nature of the measure was underlined by the fact that the terms and conditions of the Act (1919, 9 & 10 George V, ch. xlix) could be varied after four years by Order of the President of the Local Government Board, following representations from affected parties. Completed in 1921, the capital cost was only £380,000 compared with the inevitable delays and estimated cost of £2.5 million for the construction of an impounding scheme to provide a similar quantity of supply water (Hawson 1968).

1.4 The search for a more coherent approach

1.4.1 Piecemeal development

No matter how significant the precedents, they arose on an ad hoc basis. Taken together, the schemes did not represent a coherent policy, developed from a basis of expanding knowledge. Not only was there often inadequate information on rainfall and stream flow, but the statistics, even when available, were collected in such diverse ways as to exclude meaningful comparison between river basins. Many commentators argued that there was no alternative to a government department, or an ad hoc national water commission, being given the responsibility for collecting the relevant statistical information and for adjudicating on water issues (Prescot Hill 1906; Sandeman 1913).

1.4.2 The report of the Water Power Resources Committee

The question of compensation water was one of many aspects reviewed by the Water Power Resources Committee, immediately after the first world war. Appointed by the President of the Board of Trade, the members soon discovered that they could not adequately assess the potential for hydro-electric power development without looking more widely at the steps being taken to ensure that 'the water resources of the country are properly conserved and fully and systematically utilised for all purposes'. The committee became a Joint Committee of the Board of Trade and Ministry of Health. In its final report of 1921, the Joint Committee criticised the methods commonly used for assessing compensation water, arguing that greater attention should be paid to the character of flow in the natural river and to the requirements of all riparian users. Because of the wide variety of situations encountered, there was no alternative to deciding the amount and management of compensation water on an individual basis (Water Power Resources Committee 1921).

The Committee's report encouraged the British Waterworks Association in 1923 to pass a resolution, describing how the existing practice of assessing compensation flow had led to the 'unnecessary expenditure of millions of pounds and enormous waste of water'. The only public response from the Ministry of Health was to appoint an Advisory Committee on Water in 1922, made up of representatives of the Association, the Institution of Water Engineers, and the Water Companies Association, together with 2 Welsh members. It met under the chairmanship of a Ministry official (Public Record Office (PRO), HLG 50, 81 & 2142).

Whilst everyone on the Advisory Committee agreed that the optimal solution would be to grant the Minister powers to issue Provisional Orders, setting out the basis for deciding compensation flow, based on efficient stream gauging, there was little chance of Parliament agreeing to such an administrative change without a universally acceptable method of assessing compensation flow being identified. To that end, a technical sub-committee was appointed to find 'a formula to cover as many cases as possible'.

In its report of 1930, the sub-committee argued that the amounts of water allotted for compensation purposes were nearly always too generous. Discharge should be determined by four factors, namely rainfall, the loss due to evaporation and absorption, the character of stream flow, and the user factor. The report put forward the formula whereby:

$$C = UK(0.8R - L)$$

where C represents the compensation water, U the user factor, R the long period average annual rainfall, and L the average rainfall loss in a three dry year period. The stream characteristic K is calculated as the average daily flow on those days when the flow is equal to or below the mean gauged flow as a ratio of the mean daily gauged flow. Thus flashy streams have low K values and stable, constant flow regimes have K values approaching unity. The subcommittee suggested user factors ranging from 0.7 for a fully industrialised river to 0.35 for a rural class of riparian user. Using the assumptions made by the sub-committee, the overall effect of using the formula was likely to be a reduction in the amount of compensation water required, and a consequent increase in the volume available to undertakers and the cost-effectiveness of existing and future schemes (Ministry of Health 1930).

1.4.3 The draft White Paper

The Minister of Health believed the proposals were unanswerable, and he called for immediate legislation to effect the changes in the basis of assessment. His officials were much less enthusiastic, and their warnings about the intricate and 'hotly controversial' nature of the question were soon borne out (PRO, HLG 50, 79). The recommendations could not, however, be shelved. By the spring of 1934, the country was suffering from the most severe drought for 50 years. In April, a Water Supply (Exceptional Shortage Orders) Bill was passed, giving the Minister powers to issue orders, permitting undertakers to use new sources, and to suspend or modify restrictions and obligations related to compensation water and public water supplies. Each order was to last for a maximum of 6 months (PRO, HLG 50, 64 & PREM 1, 160; Act 1934, 24 & 25 George V, ch. 20).

The Ministry hoped the drought would 'give water undertakers valuable ammunition for a fresh attack on antiquated provisions'. A White Paper was drafted, the central purpose of which was to confer on the Minister the role of a central co-ordinating authority, empowered to regulate the acquisition of water rights and, inter alia, the adjustment of compensation flows. The cumbersome and costly business of promoting Private Bills would be discarded. Subject to parliamentary safeguards, and in consultation with all interests, the Minister would secure the improvements through ministerial orders (PRO, CAB 24, 251 & 254, & CAB 23, 80).

When the draft White Paper was submitted to the Cabinet, there were criticisms of the wide powers sought by the Minister. The President of the Board of Trade, and the Minister of Agriculture and Fisheries criticised the Paper for its being written 'almost entirely from the point of view of water undertakers'. It was bound to excite 'violent criticism and attack'. The Minister was refused permission to publish the White Paper, and the question of 'measures for the better conservation and organisation of water resources and supplies' was referred instead to a Joint Committee of both Houses of Parliament (PRO, HLG 50, 73 & CAB, 23, 81). The way in which the matter was referred to the Joint Committee, and the absence of any guidance from the Government, did not augur well for the Ministry (Sheail 1983).

1.4.4 The report of the Joint Committee

In its report of 1936, the Joint Committee conceded that the rough-and-ready method of allocating a third of the available yield to compensation and two-thirds to supply purposes was most unsatisfactory, insofar as little distinction was drawn between the requirements of a flashy and steady stream-flow, and between an industrialised and more rural watercourse. The Committee nevertheless rejected the formula put forward by the Minister's Advisory Committee, and endorsed by the Ministry of Health. In the case of 10 rivers which the Committee examined, the formula would result in a reduction of 64% in compensation water on an unindustrialised, flashy river, and of 25% on a highly industrialised, steady river. The Joint Committee doubted whether Parliament could have been so seriously in error when the compensation awards were fixed initially. In one of the cases studied, the reduction would have led to an award that was even lower than the average dry weather flow in the driest month in five consecutive years. Such a level was well below the legitimate requirements of riparian owners.

When unsatisfactory awards had been made, the Joint Committee believed they had arisen largely from inadequate information on rainfall and run-off. Even if the proposed formula were adopted, these data would still be lacking. Even when obtained, conditions were likely to vary so much that each award should be based on local circumstances. They should take account of (i) the character and flow of the stream; (ii) its present use for industry, fisheries, and 'the probability of future industrial development'; (iii) the range of riparian and other landed interests present; and (iv) the need to prescribe a minimum amount below which compensation should not be fixed (Joint Select Committee 1936).

Because of the way water management affected property rights so closely, the Joint Committee rejected any system of ministerial orders. Not only should Parliament continue to be responsible for authorising any changes in compensation water, but an award, hitherto accepted as final, should only be altered in the most exceptional and compelling circumstances. The Committee recommended that a Central Advisory Water Committee should be appointed by the Minister to collect and disseminate information. Made up of representatives of the relevant departments and outside bodies, it would advise Ministers and Parliamentary committees on the merits of Water Bills.

1.4.5 The Water Act, 1945

It was not until the fourth autumn of war, and 'a major upheaval in public opinion' towards the role of central government that an extension of ministerial powers could be taken for granted. As officials and Ministers considered how to exploit the new mood in terms of planning and other sectors of domestic government, they found themselves reviewing the options identified in the inter-war years. A White Paper on national water policy, published in April 1944, recommended that Parliament should delegate considerable powers of direction to the Ministry of Health (Ministry of Health 1944; Sheail 1983). The White Paper formed the basis of the Water Act of the following year (Act 1945, 8 & 9 George VI, ch. 42).

The White Paper endorsed the principles set out by the Joint Select Committee in 1936, as they related to the assessment of compensation water. Under the Act, a statutory undertaker could acquire water by agreement or by compulsory powers where the Minister gave his consent. Before issuing an order, the Minister had to be assured that the undertaker could provide and maintain an adequate quantity of compensation water according to the procedures laid down in a schedule to the Act.

Although water undertakers welcomed the introduction of the Order procedure rights, as an alternative to the time-consuming and expensive procedure by Private Bills, they complained that nothing had been done to simplify the problems of arriving at an equitable assessment of compensation water. For example, undertakers had always challenged the recommendation of the Joint Committee in 1936 that special attention should be paid to the possibilities of future industrial use of the watercourses. They welcomed therefore the wording of the Act, which seemed to treat the future needs of industry no differently from those of water undertakers and other users. On the other hand, the Act implied that even greater emphasis should be placed on forecasting future requirements than previously suggested. There was considerable uncertainty as to how the Minister would interpret this requirement in assessing individual schemes (Risbridger 1962). Most seriously of all, the Act did not grant the Minister powers to issue Orders for varying the quantity or manner of discharge of any compensation water granted under previous Acts, except where the consent of interested parties was obtained.

1.5 Compensation water and the long distance transfer of water

1.5.1 Early precedents

The allocation of water for compensation purposes had to take account of the increasing practice of transferring water from one catchment area to another. The adjustment of compensation flows often provided the means by which the interests of the water undertaker could be reconciled with those of the impounded watercourses.

The increasing scarcity of potable water in many towns of the nineteenth century led to a growing number of schemes that envisaged the transference of water over very long distances - from one river basin to another. Some intimation of the outcry that would greet such proposals was given by the opposition to a plan to transfer 1 mgd of spring water from the headwaters of the river Thames to the Severn valley in 1855. During a debate on the second reading of the Cheltenham and Gloucestershire Water Bill, opponents warned of how it would be regarded as a precedent, and the 'health, cleanliness, and comforts of all the towns and villages, including the metropolis' would suffer. Whereas a town in the Thames valley would use and return the water, albeit polluted, to the river, not a drop would be returned under the Bill. Shoals and flats would appear, and the proportion of sewage to pure water would rise. The Bill was rejected by 118 votes to 88 votes (Hansard, Commons, 3rd series, 177, 490-95). In a report of 1869, the Royal Commission on Water Supply to the Metropolis affirmed that it was wrong in principle that any one town or district should take possession of the gathering grounds belonging geographically to another (Royal Commission 1869).

It was a sentiment frequently voiced during the promotion of Bills by the Corporations of Manchester (1878-79), Liverpool (1880), and Birmingham (1892) respectively to impound Lake Thirlmere in the Lake District, and to construct reservoirs in the Vyrnwy and the Elan and Claerwen valleys in Wales. Together, the schemes represented a new phase in the scale of water undertakings, both in terms of the distances involved and the quantities of land and water to be exploited. Not only were the Welsh gathering-grounds 70 miles from Birmingham, but their area of 70 square miles far exceeded the limits of the city (Briggs 1952). As the city's consulting engineer, Sir James Mansergh, remarked, 'where you have to go, for a large town, a long distance, you must have at the end of it an area that will produce a supply commensurate with the expense of making the aqueducts' (HLRO, Commons Select Committee, minutes of evidence, 1892, vols 2-4).

The Bills raised such large questions of public importance that each was opposed at the second reading, and exceptional steps were taken to ensure close scrutiny of such questions as compensation before the Parliamentary Select Committees. In the same way as the English paid for Welsh coal and iron, a Welsh member demanded that Birmingham should make 'some compensation for the valuable public and immemorial rights'. Water undertakers always dismissed such a 'watershed doctrine' as impractical and absurd. In the debate, the member for Birmingham, Joseph Chamberlain, retorted that the desired water 'came from Heaven and goes to the sea, and no more belongs to Welshmen than anybody else who stands in need of it'. Having accepted the need for schemes, the Select Committee endeavoured to award adequate safeguards in terms of compensation.

In deciding the level of compensation flow from the Thirlmere scheme, particular importance was attached to preserving the amenity of the lake. Not only was a maximum of 50 mgd specified for supply purposes, and a minimum of 5.5 mgd for compensation water, but the Act (1879, 42 Victoria, cap. xxxvi) stipulated the height of the overflow sill from the lake. Because the lake became so shallow in times of drought, and the water turbid and objectionable to drink, the sill, and thereby the maximum height of the lake were raised in 1915. When the legality of this action was challenged, a Bill was promoted to give it statutory effect (HLRO, Lords Select Committee, minutes of evidence, 1924, group N; Act 1924, 14 & 15 George V, ch. xcv).

1.5.2 The mid-Wales schemes

In assessing the optimum compensation flow from the Vyrnwy scheme, Parliament found the downstream interests divided (Parliamentary Papers, 1880, vol. 10). Navigation interests stressed the dangers posed to the river Severn - this 'great artery of the trade and commerce of the Midland Counties'. The riparian interests between Tewkesbury and Gloucester, however, petitioned in favour of the Bill, arguing that it 'would tend to regulate the flow of water down the river Severn and diminish the floods by which much damage was done to their property' (Hansard, Commons, 3rd series, 250, 1278-95). Between sittings of the Select Committees, Liverpool Corporation agreed to raise the amount of compensation water from 8 mgd to 10 mgd (about a quarter of the available yield). It also created a precedent of offering an additional 1280 mg of water, to be released between 28 February and 1 November each year 'for flushing purposes'. The Severn Navigation Commissioners could ask for 40 mgd to be discharged in each of the 8 months over 4 successive days in each month, with at least 14 days between each flush. As an alternative, the water could be released in 2 periods of 2 successive days, with not less than 7 days between them (Act 1880, 43 & 44 Victoria, cap. cxliii).

During the promotion of the Birmingham Bill, the Corporation resisted the adoption of the same ratio as adopted in the Pennines. The principal landowner in the catchment had kept rainfall records for over 20 years, which indicated an average rainfall of 69 inches per annum. On this basis, the Corporation estimated an average yield of 99 mgd, and offered 22.5 mgd in compensation water. The opposition was, however, so strong that, during the Bill's promotion, the latter was increased to 27 mgd, or 26% of the yield. The Conservators of the river Wye could direct 5 mgd of this compensation water to be accumulated for a period of up to 21 days, and then discharged over 2 days in an even flow (Act 1892, 55 & 56 Victoria, cap. clxxviii).

The Birmingham Bill was the first occasion when considerable attention had to be paid to the needs of the fisheries, as opposed to industry, in assessing compensation needs. The Elan and Claerwen valleys included some of the finest spawning grounds for salmon on the river Wye. Not only was it impractical to build fish passes for the 6 projected dams of over 95 feet in height, but it would have been too costly. In a report on the Bill, the Board of Trade, on behalf of the fisheries interests, recommended that the Corporation should set up a fund for such purposes as the removal of obstacles to the ascent of fish on other tributaries of the Wye (Parliamentary Papers 1892, vol. 72). Under the Act, the sum of £7,500 was paid to the Board of Trade, to be held in trust for the improvement of the fisheries by the Conservators of the Wye Fisheries District (Mansergh & Mansergh 1912).

1.5.3 The Haweswater scheme

An even more flexible approach to the fishery question was adopted in 1919, when the Manchester Corporation sought powers to impound and enlarge Haweswater in the Lake District. The rivers Eamont and Lowther had several long stretches of gentle gradient, where an assured, minimum flow, with periodic freshets of water, would create much better conditions for fish breeding than the natural dry-weather flow with occasional heavy floods. On this premise, a clause was formulated outside the Parliamentary Committee Rooms by representatives of the Corporation, the trustees of the Lowther estates, and the Board of Agriculture and Fisheries (BAF) (acting for the Eden Fishery Board). The chief difficulty was in agreeing on a minimum and maximum daily flow, and the total annual discharge. In a complicated compromise, the trustees of the Lowther estate and the Eden Fishery Board could jointly direct the Corporation to discharge any amount of water, provided it did not exceed 18 mg in one day, or 3285 mg in 12 consecutive months. The latter was the equivalent of an average 9 mgd, or a ninth of the available yield. The Corporation undertook to pay £19,000 to the BAF for the use of the Fishery Board in constructing weirs and fish passes (HLRO, Commons Select Committee, 1919, minutes of evidence, group A).

For the first time, an Act had stipulated the total quantity of water to be discharged each year, as well as making provisions for the daily compensation flow. There were further safeguards, if the trustees and

Fishery Board believed them to be necessary. They could jointly direct the Corporation to double the maximum discharge to 32 mg in one day, and the annual discharge to 5110 mg (an average of 14 mgd) over a year. Alternatively, they could require the Corporation to contribute a further £15,000 towards improvements to the fisheries. In the event of their making use of both options, the additional payment would be reduced by £3,000 for every 365 mg discharged in excess of 3285 mg per annum (Act 1919, 9 & 10 George V, ch. cxix). In practice, the formula meant that, if the trustees and the Board jointly decided that, by incurring additional expense on improvements, a lower daily discharge than 14 mg would suffice to maintain the fisheries, they had the right to require the Corporation to increase its monetary contribution by £3,000 for every reduction of one mg in the average daily discharge, down to a minimum of 9 mgd (Holme Lewis 1921).

The precedents established by the Haweswater scheme were adopted in 1923, as part of the Act designed to raise the level of the sill of Lake Thirlmere. In place of the obligation to discharge 5.5 mgd, irrespective of whether all the water was required by downstream interests, the Corporation was obliged to send down only 3 mgd in an even, continuous flow and, when requested by the Derwent Fishery Board, an additional 4 mgd in October, 3 mgd in November, and a further 4 mgd at other times of the year, when directed by the millowners' committee. These requirements were subject to a maximum discharge of 605 mg in the year up to 31 March, and 391 mg in the 6 months up to 30 September. The sum of £5,600 would be paid to the Ministry of Agriculture and Fisheries for the use of the Fishery Board in maintaining and improving the fisheries.

By these and other precedents, the abstraction of water from comparatively remote, upland areas led to a considerable extension of the factors that had to be taken into account when deciding the volume and manner of discharge of compensation flow. Not only was the equivalent of the 'dry weather flow' released at all times, but periodic or seasonal floods were simulated, albeit in a predetermined and regulated manner, where this was thought to be in the interests of the river-user. The assessment of compensation water had become more sophisticated insofar as new schemes were concerned.

1.6 Scottish precedents - a case study of Edinburgh supply schemes

1.6.1 The Talla scheme

Further precedents were established for Scotland in the course of promoting a series of reservoir schemes affecting Edinburgh. Using the records of the promoting bodies and those of Parliament and government departments, the case study will look in some detail at the circumstances in which the precedents were allowed.

Amid considerable controversy, the Edinburgh and District Water Trustees decided in 1889 that the next phase in the supply of water to Edinburgh should be the impoundment of Talla Burn, a tributary of the Tweed in Peeblesshire (Figure A1.1). There were 9 petitions against the Bill promoting the scheme in the House of Lords, and 2 in the Commons. All were withdrawn, the Bill was passed in 1895 (58 Victoria, cap. xxvii), construction work began in 1897 and was completed in 1905.

The Trustees satisfied the opposition to the scheme by inserting clauses in the Bill affecting the related topics of compensation water and fisheries. Whilst the fishery, industrial and other river interests agreed [illegible] the usual practice of setting aside a third of

the available yield as compensation water, as calculated on the basis of the rainfall of the catchment, they wanted an assurance that the amount of rainfall would be assessed as accurately as possible. As a concession, the Trustees took the unprecedented step of agreeing to instal rain gauges in each part of the catchment. The records made over 7 years would provide a basis for an arbiter appointed by the Trustees, and another by the river interests, to estimate a level of compensation flow that would represent a third of the available rainfall. In the interim period, 4 mgd of compensation water would be discharged to the Talla, and thereby to the Tweed.

The gauges indicated an annual average rainfall of 62.51 inches. Drawing on experience elsewhere, the arbiters introduced a correction factor of 4% to reflect the average over a longer period, namely 65 inches. From this, they deducted 15 inches to represent losses caused by evaporation and transpiration. Under the Act, an oversman could be appointed in the event of a dispute between the arbiters. This provision was adopted in order to decide the available yield in the driest 3 consecutive years likely to be incurred. The oversman, James Mansergh, decided that a deduction of 12 inches should be made to take account of this. On the basis of 38 inches of rainfall being available, it was calculated that the yield of the scheme would be 14.598 mgd, of which 4.866 mgd or a third should be set aside for compensation purposes.

In a second concession, the Trustees had agreed to the appointment of arbiters to assess how seriously the salmon fishery of the Tweed would be affected by impoundment. The river interests claimed £8,000 in money compensation, the arbiters differed, and an oversman was appointed. He awarded £500 for the loss of spawning grounds above the dam, and £1,760 for the damage sustained generally by the Tweed fisheries. It is not known what data and criteria he used, but the cost of making the arbitration far exceeded the amount of the award (Edinburgh City Chambers, minutes of Trustees, 1894-95; Tait 1905).

Whilst the device of arbitration had enabled the Bill to be promoted during its later stages as an Unopposed Bill (HLRO, Select Committee 1895, minutes of evidence), and had obviated the need for Parliamentary Select Committees to adjudicate between the contending parties, the outcome of arbitration highlighted the need for many more environmental data, and particularly for river flow records and a greater understanding of the water requirements of migratory fish. So much controversy stemmed from ignorance on those fundamental questions in river management.

1.6.2 The revision of the Talla compensation levels

By the 1930s, further supplies were needed. It had always been envisaged that the second stage of development would be the diversion of water from the nearby Fruid valley (Figure A1.1) into the Talla reservoir, the embankment of which would be raised. The aqueduct from Talla to Fairmilehead, outside Edinburgh, had been planned and built on this assumption. Further studies in the 1930s indicated that it would be much more cost effective to construct a new reservoir in the Fruid valley, which could hold 6000 mg, compared with an addition of only 1000 mg in the enlarged Talla reservoir. Confronted with the cost of building a new reservoir, and the considerable difficulties of forecasting future demand at a time of economic malaise and a falling birth-rate, the Corporation which had taken over responsibility for water suppplies in 1924 looked for ways of postponing its construction for as long as possible.

The Corporation succeeded in this objective by resorting to two types of expediency. In 1934, it proposed that the entire 5 mgd of compensation water, allotted under the Act of 1895, should be taken over for supply purposes, in return for money payments to the river interests. If the Corporation's obligations could be commuted in this way, the construction of the Fruid reservoir could probably be postponed for 20 years. When a Provisional Order to this effect was promoted, it was opposed and therefore submitted by the Secretary of State for Scotland to a Commission of Inquiry composed of equal numbers of Scottish members of both Houses of Parliament (City Chambers, Edinburgh Corporation Provisional Order, 1934, 1 vol.; Scottish Record Office (SRO), HH 33, 700).

In the negotiations of 1934, the Corporation stressed how the elimination of the award of 5 mgd would cause less damage to the fisheries than the impoundment of the headwaters of a further tributary, the Fruid. The Tweed Commissioners agreed that it was the lesser of two evils, and the draft Provisional Order was based on this agreement. The Fishery Board for Scotland was less easily satisfied. Although the Tweed Commissioners had reserved the right to review the agreement after 10 years, and to appoint arbiters to assess any deterioration in fishing, the Board warned of how it would be impossible 'to separate the effects of this particular loss of water from those of the many other factors which might affect the fish of the river in the interval'. The Board withdrew its opposition, however, when the Corporation offered to contribute £5,000 towards 'compensating improvements of the Tweed salmon fishings', namely fish passes that would benefit the entire river.

The Peebles County Council, supported by the Association of County Councils in Scotland, alone persisted in its opposition. It alleged that a complete cancellation of all obligations to supply compensation water would create a precedent and have '[illegible] and far-reaching results'. When the Provisional Order came before the Commission of Inquiry, legal counsel for the Corporation conceded that the Order was 'out of line with what is established practice', but could be justified by its exceptional nature. For a sum of £20,000, the Corporation had been able to satisfy all interested parties, except the County Council which had no direct interest in the river. Not only had the Corporation avoided an outlay of at least £500,000 in constructing a new reservoir which might not be needed for many years, but it had prevented the destruction of the salmon redds on the headwaters of the Fruid.

In his speech to the Inquiry, legal counsel for the Peebles County Council (T M Cooper) stressed how, far from finding itself in a unique position, Edinburgh had simply alleged that it needed a little more water, and possibly more later, but did not want to spend money. If the Order was passed, practically every water undertaker would apply to have its water-compensation obligations wiped out, and 'the whole basis of water legislation will undergo a revolutionary change'. A river should be treated as a natural asset. It was, in Cooper's words,

> an asset which has potentialities for public health purposes, for drainage purposes, for water supply purposes, for power purposes. One cannot tell in course of time for what purpose. It is a natural asset which is not to be made the subject of huxtering bargains between an acquiring authority and a person who happens to have owned or leased a piece of salmon fishing along its bank.

Because the counsel for the opposition to the Order led no evidence, and based his argument entirely on a matter of principle, the promoters had no right of reply to Cooper's speech (SRO, HH 34,34).

Lest the Order should be taken as a precedent by other undertakers, the Commissioners rejected it. A member of the Commission of Inquiry later recalled how Cooper's 'most powerful and eloquent plea ..... went very far towards turning, if it did not entirely turn, the scale and influence the minds of the Commissioners' (Hansard, Commons, 307, 1848-55). Acutely disappointed that its attempts to conciliate the opposition had failed, the Corporation had to find a formula whereby the concept of compensation water was preserved, and yet more water was diverted to the public supply. It did so and, this time, the Peebles County Council raised no objection to the Order.

The Corporation's water engineer had little room for manoeuvre. During the promotion of the earlier Order, the Corporation had insisted that all the 5 mgd of compensation water was required for supply purposes if the construction of the Fruid reservoir was to be postponed, and that any fraction that could be spared for the river would, in practice, have a negligible effect. Under these constraints, the engineer accordingly proposed that 3.65 mgd, namely three-quarters of the previous amount, should be discharged as compensation water in the months of May to September, and that the remainder and all the water at other times of the year should be diverted to supply purposes. Calculated over a year, the average proportion of the available yield devoted to compensation (8.5%) would be similar to that adopted under the Haweswater scheme, promoted in 1919.

The concession, together with the money payments to the various river interests (including £15,000 to the Peebles County Council for the installation of sewage works), led to the withdrawal of almost all the opposition (City Chambers, Edinburgh Corporation Provisional Order, 1935, 1 vol.; SRO, HH 34,35). The Fishery Board for Scotland regarded the new Order as a great improvement, insofar as there would now be a regulated flow in the months when pollution and damage to fishing were most likely to occur. The Commission of Inquiry approved the Order, subject to a provision being made whereby a further review of the compensation issue should be made if and when powers were sought to abstract further water from the Tweed (SRO, HH 81, 29; Act, 1936, 26 George V & 1 Edward VIII, ch. vi).

The attempt to eliminate, and then reduce, the compensation water granted under the 1895 Act highlighted the penalties likely to be incurred by a water undertaker who sought to create precedents on a point of principle. In seeking to adjudicate between the contending parties, Parliament had to bear in mind the ramifications of its decisions, not only for the scheme in contention but for water resource development generally.

1.6.3 The Fruid-Menzion intakes

By the late 1940s, a second expedient was needed if the construction of the Fruid reservoir was to be postponed. The Corporation water engineer, George Baxter, proposed that an aqueduct should be built, largely as a tunnel, from a diversion weir on the Fruid Burn to the Talla reservoir. An additional 6 mgd would be derived from the intake, and another constructed where the tunnel passed under the Menzion Burn. By the time the Order to promote the scheme reached Parliament in 1948, the opposition had been met, and the works were completed in 1952 (Statutory Instrument, 1949, No. 149 (s. 11).

During negotiations, the Corporation emphasised the steps being taken to mitigate the effects of abstraction. None would be permitted unless there was twice the dry weather flow in the burns, as determined on the basis of half a century of gauge records (namely 2.5 mgd on the Fruid and 0.625 mgd on the Menzion). The upper limit set on abstraction corresponded with the maximum levels of economic abstraction. The Corporation also offered to provide freshets, over which it would exercise complete discretion as to timing and quantity. When the Fisheries Division of the Scottish Home Department suggested 'some minimum requirement', Baxter warned of how, 'once you take the provision of the necessary quantities of water out of the hands of the man on the spot and constitute a compulsory provision during specific periods, the water may be simply wasted'. In the event, the Order required freshets of not less than 15 mgd on the Fruid and 4 mgd on the Menzion to be provided some time between 28 September and 30 November each year. There would be at least one period of 12 hours, or 2 of 6 hours, when 'reasonably practicable and provided the natural flow in the two streams is sufficient'.

In addition to these concessions, the Corporation made payments totalling £22,000, the largest of which was £14,500 to the Tweed Commissioners in respect of the salmon fisheries. Baxter later recalled how the Corporation 'never succeeded in obtaining any satisfactory or rational explanation of the basis of the Commissioners' claim'. There was then not much information available on 'how many fish were likely to be affected'. The claim seemed to be based on the payment of £7,500 for the loss of compensation water from Talla in 1936, and the extent to which sterling had depreciated since that time.

In assessing the reasonableness of the sums claimed, account had to be taken of the cost in terms of the alternatives open to the Corporation and the long-term impact of the works on fishing. Despite a strong dislike of 'having to buy these people off', Baxter realised that, if they persisted in their opposition, the Secretary of State would have to convene a Commission of Inquiry, and there would inevitably be a delay in starting the work. In later correspondence, Baxter also commented on how, if an Inquiry had been held, 'the likelihood is that we should have been obliged to increase our lower limit of abstraction ..... and we might have lost anything from 0.5 to 1 mgd. The total compensation payment is, therefore, cheap'.

Whatever the Corporation's public stance, Baxter conceded to the Water Committee in January 1948 that the sum of £14,500 was unlikely to cover the cost of injury to the salmon fishing interests. In justifying the sums agreed in negotiation, he emphasised how the Tweed was recognised generally as 'the most prolific and famous salmon fishing river in Great Britain'. Losses were likely both on the affected streams, and further downstream. Spawn-laden fish would enter the stretches between the Tweed and the intakes, and become stranded. The maximum quantities to be abstracted represented the flow of a large-sized river and would, in the more moderate-sized floods in which salmon 'run', lead to a lower depth of water over the various caulds that obstructed the Tweed downstream of Peebles. This reduced depth could make all the difference to the salmon 'running', or continuing to lie below the caulds at the critical time. The provision or improvement of fish-passes would be both expensive and risky work.

1.6.4 The Fruid scheme

Whilst circumstances forced the Corporation to be innovative in reconciling the disparate demands made on the stream water, Baxter was unusually well equipped as a water engineer for this task. As he remarked in correspondence in 1949, 'I do a lot of salmon fishing myself, and have devoted a lot of study to the subject'. Forty years of experience in the field of public water supply, holidays spent fishing, and membership of the

Statutory Fisheries Committee (established under the Hydro-Electric Development (Scotland) Act of 1943) were drawn on in compiling a paper, which he read to a meeting of the Institution of Civil Engineers in April 1961 (Baxter 1961).

Having analysed the flow of 15 rivers, 13 of which were Scottish, and considered the life history of migratory fish, Baxter concluded in his paper that it was quite inappropriate to assess compensation water as a proportion of available yield, or of some other non-biological factor. The natural and logical basis of assessment was the height of water needed for the fish to enter the river section and spawn. Account also had to be taken of the feeding habits of the parr, and of the rates of flow required to keep the river in a healthy state. The height of the water required was generally no greater than that represented by the dry weather flow, subject to the maintenance of a minimum flow of an eighth of the average daily flow (ADF) during periods of hot weather. This basic minimum seasonal flow should be supplemented by the release of freshets, provided from a bulk allocation and discharged at the discretion of the river interests.

The concepts were applied and further refined in connection with the planning of the Fruid reservoir scheme. Although it believed there was sufficient water to satisfy needs for a further 10 years, the Waterworks Committee decided to commission, in 1958, a report of what should comprise the next phase in the development of the Tweed works. The report was written by the Corporation's water engineer and Baxter, who had, by this time, become a consultant engineer to the Corporation's consultants, Cuthbertson and Associates of Edinburgh. They estimated that the long-term average flow of the Fruid Burn was 15.8 mgd, of which it was economically practicable to impound 13.7 mgd. About 4.5 mgd of this amount was already utilised under the Order of 1948.

Because of the importance of the fisheries and the inroads already made by the Talla scheme, rather more compensation water would have to be given than was 'customary in modern practice'. Baxter calculated that, on average, the flow fell 'to below a quarter of the long-term average flow for 60 days a year on the Fruid, with variations from 20 to 100 days, and 2 mgd or just on an eighth of the long-term average was a commonly occurring figure'. He accordingly proposed that 4.1 mgd should be set aside as compensation water, namely double the normal minimum flow and almost 3.5 times the minimum flow previously recorded at the site of the proposed dam. In order to make the greatest use of this water for spawning purposes, Baxter proposed a daily allocation equivalent of 3.5 mgd, and an additional block allocation of 200 mg per annum in the form of 28 freshets.

With these deductions made, the additional amount of water to be derived from the valley would be only 5.1 mgd - an amount insufficient to warrant the cost of the works. The report accordingly recommended that intakes should also be constructed on two further tributaries of the Tweed, namely the Hawkshaw and Fingland Burns (Figure A1.1), and a further 2.1 mgd diverted from these streams into the Fruid reservoir. The severe drought of 1959, when the Corporation's reservoirs were reduced to about 35 days' supply, persuaded the Corporation to promote such a scheme with the minimum of delay. An Order was approved without the need for a Commission of Inquiry in 1962. In order to meet the opposition, the amount available for public supply was reduced to 4.88 mgd - slightly less than what the Corporation had initially argued was the economic minimum level of abstraction. The outlay of £300,000 per mgd was nevertheless considered a relatively low unit capital cost by the time the impoundment of the waters began in April 1967.

The Tweed River Purification Board acted on behalf of all the major river interests during negotiations over the compensation water issue. It accepted the concept of a basic allowance, plus freshets. The basic allocation was to be 1161.70 mg per annum, or an average of 3.18 mgd, with at least 12% of the ADF discharged between mid-December and the last day of February, 20% in March and April, and between September and mid-December, and 25% between May and August, when 'the needs of the river and of the fry and parr life are at their maximum'.

A block allocation of 178.23 mg per annum, or an average of 0.49 mgd, was to be made for freshets. There were to be no more than 28 per annum, and the Corporation was to be given at least 48 hours notice of a freshet being required, except in an acknowledged emergency. Unless otherwise agreed, each was to extend over 12 hours at full rate, and 6 hours at half rate (the tailing). Including the basic compensation water, the two freshets per month in March and April would each represent 70% of the ADF, the four per month of May to September would represent 100%, and the four of October 70%.

Baxter often warned the river interests of how 'any insistence by them on more compensation water being provided' would only hasten the day when Edinburgh would have to look to some further tributary of the Tweed for more water. The impounding scheme would only affect the higher rates of flow, and could lead to a reduction or even prevention of flooding downstream at Peebles. The Purification Board retorted that the scheme would exacerbate an already unsatisfactory position, caused by the absence of any compensation water from the Talla reservoir in winter. Over the previous 60 years, the volume of water discharged from that part of the river basin had fallen from 33.3 to 10% of the annual gross yield of the Tweed, causing heavy silting to occur. To help remedy the situation, a block allocation of 200 mg per annum should be made from the Talla reservoir in the form of freshets. Although the Corporation protested that money compensation had already been paid on the earlier schemes, it was conceded that the original assessment of the annual rainfall of 65 inches had been too low. Records for the previous 60 years suggested that it was about 70 inches. The Corporation could afford to make some concessions.

The Order implementing the Fruid scheme was accordingly extended to give the Purification Board the right to request up to 220 mg per annum, or an average of 0.06 mgd, from the Talla or Fruid reservoirs, or partly from both. If the allocation was set against the Talla, the average daily discharge of compensation water was 11.8% of the available yield, and 26.8% of the Fruid. Unless otherwise agreed, the discharge of the additional allocation was not to exceed 15 mgd in any seven consecutive days, or 25% of the annual allocation in a month. In any one day, four-fifths of the water was to be discharged in a uniform and continuous flow over 12 hours, and the remainder over the ensuing 6 hours at a gradually reducing rate. With the installation of modern electronic equipment, the Corporation did not anticipate any difficulties in regulating the water (Statutory Instruments, 1962, No. 781 (s.26)).

Under the terms of the Order, the Tweed Commissioners submitted a claim for the losses that would inevitably arise from the construction of the 70 feet high dam. Baxter insisted that the claim of 1949 had been intended to cover 'the complete writing off - for all practical purposes - of the spawning potential of Menzion and Fruid', and that no further payments were envisaged by any party when the reservoir was eventually built. He had regarded the Corporation's agreement to build a fish pass in the Fruid intake as 'a gesture for the possible ascent of an odd fish or two'. At that time, little was known about the minimum flow conditions under which salmon could survive. The experience of the North of Scotland Hydro-

Electric Board was not then available. Everyone was surprised when just as many fish continued to run and spawn after the knife-edged weir had been built. Far from experiencing a loss, the Commissioners had profited to the whole extent of the compensation paid in 1949, and this fact should be taken into account in assessing any liability on the part of the Corporation under the new scheme.

The Commissioners' claim of £25,000 was designed to cover the value of the Fruid as a spawning stream, with an element to represent its role as a rearing ground. On average, 50 pairs spawned in the Fruid each year. If each produced seven adult fish, and two were left for further spawning and the other five had a commercial value of £3 each, the stream had an annual value of £750 or, at 25 years' purchase, a value of £18,750. Its value as a smolt-rearing ground was assessed at £15,000 per annum. The Corporation accepted that the assumption used in the negotiations of 1948, namely that two adult fish per spawning pair survived, should be increased to at least six, in order to take account of more recent fisheries research, but it challenged the 'number of years used to arrive at the capitalisation of the annual loss', arguing that 'salmon fishing is not particularly well-secured due to many variables arising from weather effect, heavy netting, disease and natural changes in the nature of the runs'. There was 'a considerable speculation factor involved'.

The Corporation believed that an award of £8,000 would be reasonable. It would take account of the earlier compensation awards, the improved knowledge of the survival rates of salmon, and the extent to which the regulation of water from the Fruid and Talla reservoirs would reduce flooding and assure a minimum flow in dry periods. If a hatchery were installed, and steps taken to catch and strip the fish each year, there could even be a considerable improvement in general conditions.

In the very protracted negotiations that ensued, the Tweed Commissioners reduced their claim to £22,500 in 1964, and the Corporation conceded £10,000 if this would bring about a settlement. Whilst the Corporation could have sought to repudiate the claim on the grounds that the Commissioners could not prove they had incurred any damage to their interests as statutory commissioners, Baxter reminded the Corporation that 'a further large supply scheme in the lower reaches of the Tweed' would be required by 1972. Time was very short if this objective was to be met and 'it is eminently desirable that nothing should be done to affect the reasonably good relations existing with the Commissioners, having in mind the discussions which will have to be initiated with them on the new scheme in the immediate future'. He advised the Corporation to take up the Commissioners' proposal to refer the question to arbitration. Minutes of reference to arbitration were drafted, discussions took place as to who should be appointed arbiter and, in December 1967, the Corporation suggested, in view of large-scale agreement between the parties on the facts of the claim, that a last effort at agreement be made and tedious arbitration avoided. An award of £12,000 was offered; the Commissioners reduced their claim to £15,000. As an adviser to the Corporation commented, 'we are now really in the region of horse trading'. The figure of £14,000 was agreed in June 1968, a year after the dam had been built and shortly before the Corporation's water undertakings were absorbed into the South-East Scotland Water Board.

1.6.5 The Megget scheme

The case study has traced the phased development of a group of tributaries of the river Tweed, and the extent to which departures were made from the plan envisaged in the late nineteenth century. The methods by which the Water Trustees and their successors supplied water to Edinburgh reflected a series of compromises that became progressively more sophisticated as the ability of the water engineer to manipulate large quantities of water improved, and increasing amounts of environmental information became available.

By the mid-1960s, it was realised that the last stage of the development, namely the construction of a reservoir on the headwaters of the Upper Tweed itself (Figure A1.1), was never likely to be realised. The Water Trust Trustees had envisaged, in the 1890s, a yield from all the catchments involved of 24 mgd, and the tunnel sections of the aqueduct from the Talla reservoir were designed to have a capacity of 30 mgd. Because of the lack of hydrological data at the time, the estimates were very conservative. By the time the Fruid reservoir was built and received water from Hawkshaw and Fingland Burns, the available yield would reach 29.5 mgd. The available yield of a reservoir on the Upper Tweed would be too small to warrant in itself the construction of a new aqueduct.

The Corporation and its successor turned their attention to Megget Water and St Mary's Loch, which had been considered and rejected as a source of supply in the 1880s. The sophisticated criteria laid down for the allocation of water rights, as set out in the Water Order promoted for the Megget reservoir in 1974, drew heavily on the experience gained in the adjacent catchment over the intervening 100 years (Statutory Instruments, 1974, No. 2227 (s. 201)).

1.7 Conclusions

Large-scale reservoir schemes have been promoted in Britain since the mid-nineteenth century. Far from there being a uniform approach to such questions as compensation water, imposed from above, each represented a local solution. Schemes were initiated as the need arose and bargains were made between the various interested parties. Particularly in the period up to the Water Act of 1945, the role of Parliament, Ministers and officials was confined to facilitating the search for an equitable compromise. Where this compromise could not be found, the Water Bill failed and all parties waited for the next initiative from the undertaker.

The manner in which agreements were reached over such issues as compensation water may provide insights into the character and complexity of the relationships that develop between the various agencies involved in the management of water resources and the wider environment. As a former water engineer for the Edinburgh Corporation commented,

> "the determination of the proper amount of compensation water can only be arrived at as a result of co-operation between all the interested parties, advised by experts in the various fields. The answer ultimately is a compromise worked out with an appreciation of the other man's needs and a good deal of common sense."

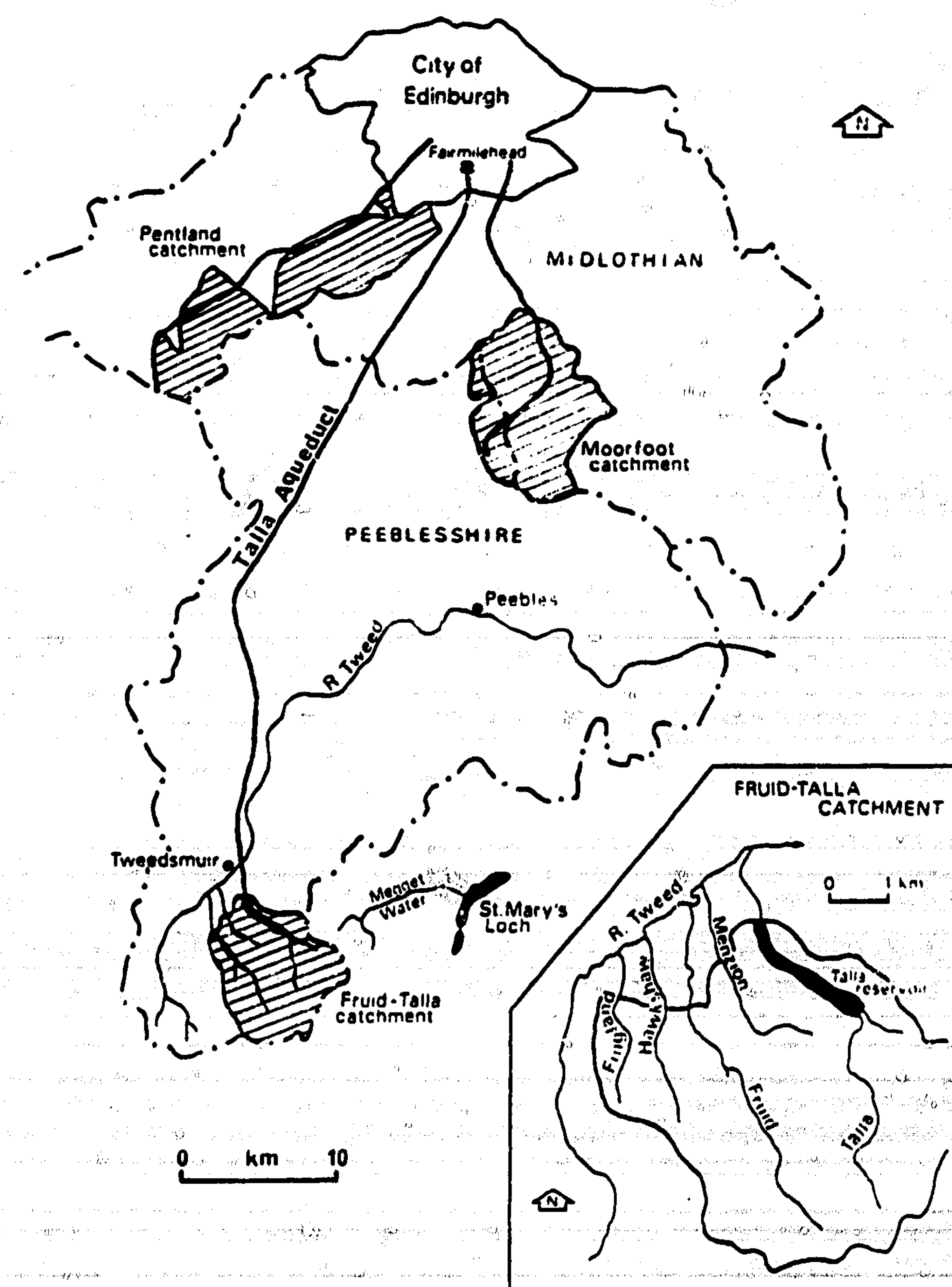

Figure A1.1 The water gathering grounds of Edinburgh in 1950's.

TABLE A1.II A SELECT CHRONOLOGY OF EVENTS

1780-1820	Main period of canal construction
1824	Bolton Waterworks Act (Belmont reservoir)
1830	Sheffield Waterworks Act (Wyming Brook)
1843	Bolton Waterworks Act (to enlarge Belmont reservoir)
1847	Waterworks Clauses Act
	Manchester Corporation Waterworks Act (Longdendale reservoirs)
1848	Manchester Corporation Waterworks Act (enlarged Longdendale scheme)
1854	Bradford Waterworks Act (Wharfe, Aire & Hewenden valley schemes)
	Manchester Corporation Waterworks Act (compensation flow adjustments in Longdendale)
1855	Glasgow Corporation Waterworks Act (Loch Katrine scheme)
1867	Sheffield Water (New Works) Act (Damflask reservoir)
1868	ROYAL COMMISSION ON WATER SUPPLY TO THE METROPOLIS
1879	Manchester Corporation Waterworks Act (Lake Thirlmere scheme)
1880	Liverpool Corporation Waterworks Act (Vyrnwy scheme)
1885	Glasgow Corporation Waterworks Act (enlarged Katrine scheme)
1888	Halifax Corporation Waterworks Act (Walshaw Dean reservoirs)
1890	Bradford Corporation Waterworks Act (Nidderdale scheme)
1892	Birmingham Corporation Water Act (Elan and Claerwen schemes)
1895	Edinburgh and District Waterworks (Additional Supply) Act (Talla scheme)
1905	Bolton Corporation Act (construction of further reservoirs)
1907	Birkenhead Corporation Water Act (Alwen and Brenig schemes)
1919	Manchester Corporation Act (Haweswater scheme)
1919	Sheffield Corporation Act (additional works)
1921	Report of WATER POWER RESOURCES COMMITTEE
1922	Bolton Corporation Act (development of further springs)
	Durham County Water Board Act (Burnhope reservoir)
1924	Manchester Corporation Act (adjustments to Thirlmere scheme)
1929	Birkenhead Corporation Act (adjustments to Alwen scheme)
1930	Report of TECHNICAL SUB-COMMITTEE OF MINISTRY OF HEALTH ADVISORY COMMITTEE ON WATER SUPPLIES
1934	Water Supply (Exceptional Shortage Orders) Act
1935	Draft WHITE PAPER rejected by Cabinet
1936	Report of the PARLIAMENTARY JOINT COMMITTEE ON WATER RESOURCES AND SUPPLIES
	Edinburgh Corporation Order Confirmation Act (to adjust compensation flows of Talla Scheme)
1945	Water Act
1949	Statutory Instrument, No. 149 (S.11) (Fruid-Menzion intakes)
1962	Statutory Instrument, No. 178 (s.26) (Fruid reservoir)
1974	Statutory Instrument, No. 2227 (s.201) (Megget reservoir)

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APPENDIX A2 A CASE STUDY OF THE MODIFICATION OF COMPENSATION AWARDS IN YORKSHIRE

In Yorkshire Water Authority, the opportunity presented by the Water Resources Act 1963 was taken up by several of the water supply authorities prior to 1974 and rationalisation of compensation provisions was continued by the Water Authority after that date. In order to understand the reasons for the changes that have been made it is necessary first to understand the differing kinds of compensation provisions that were devised over the long period (100 years or so) of reservoir construction and then to appreciate 'River Authority' and subsequently 'Water Authority' thinking on the subject of compensation water assessment.

2.1 Types of Compensation Provision

In Yorkshire there are three distinct kinds of compensation provision; (i) and (ii) below are types of single purpose "compensation only" reservoirs, while type (iii) has a dual supply and compensation function.

(i) The true compensation reservoir - these reservoirs were built as full and complete compensation for the specified supply reservoirs, with the liability to discharge compensation water limited to the compensation reservoirs. They may have been constructed either as the lowest in a chain of reservoirs in one valley or alone in an adjacent valley. In either case their catchments would be of adequate size for the reservoir and the demands on it. Following the 'one third' compensation rule the catchment commonly would be half the size of the drainage area of the supply reservoir(s). Whilst the reservoir would be maintained and a reservoir keeper provided by the water undertaking, the operation of the reservoir would be controlled by a millowners committee.

(ii) The compensation water storage reservoir - these reservoirs were built by the water undertaker below the supply reservoir(s) such that they could not be used for supply but only for the storage of compensation water. The amount of discharge is fixed by the enabling Act but the liability to discharge compensation water refers to the whole works including the (upper) supply reservoirs. Two points are of special relevance here. First the catchment area and capacity of the reservoir may well be inadequate to maintain the compensation discharge in time of drought without the aid of the supply reservoir. Second, although the quantity of discharge was fixed by the Act, the manner of discharge (perhaps during working hours only) was usually in the hands of a millowners committee.

(iii) A dual purpose supply and compensation reservoir - this reservoir must maintain compensation discharges in addition to its supply function. The volume of water and method of compensation release is fixed by the enabling Act. The Act also fixed the point of measurement of compensation discharge, usually within 200 yards of the downstream face of the dam.

The water undertaking's interest in, or concern about, the discharge of compensation water very much depended on the kind of provision that was made. Likewise the kind of compensation provision determined the scope available for re-assessment of compensation provisions or redistribution of water resources.

In the case of the true compensation reservoir, the millowners' rules of operation may or may not be in their own best interests or the best interests of other r[illegible]er uses. There may be scope for improvement in the operating rules [illegible]re will be no effect on the water available for public supply un[illegible]e reservoir can be operated to allow for a river abstraction down[illegible]n. Exceptionally, it might be reasonable to permit some abstraction [illegible] the reservoir itself.

For a compensation water storage reservoir, the water supply authority's worry is that in time of drought it may be called upon to make good its deficiencies from the supply reservoir. Some protection against this is desirable.

Where a single reservoir is used for both supply and compensation, the water supply authority will wish to maximise the amount of water available for public supply and in time of drought any reduction in compensation water discharge will increase the amount available for public supply. It is here that a permanent reduction in compensation discharge has its most beneficial effect on water supply use; it will definitely increase the amount available for supply, whereas in the case of the compensation storage reservoir it merely reduces the probability of having to draw on the upstream supply reservoir for compensation purposes.

As mentioned above, advantage h[illegible] been taken of the opportunities afforded by the Water Resources Act [illegible] change the compensation discharge requirements of many of Yorkshire's reservoirs and examples illustrative of many of the points made above are now described.

2.2 Case study examples

2.2.1. Chang[illegible] of use of compensation reservoir

Grimwith reservoir situated on the River Dibb, a tributary of the River Wharfe, was built as a compensation reservoir in respect of the Barden and Chelker reservoirs supplying Bradford. Its operation was in the hands of the Wharfe Millowners Committee which by 1965 was reduced to three members. Since voting on the Committee was according to the feet of head available to the turbines of the members, all control was vested in the Secretary of the mill which had 22 feet of head against the 10 feet and 11 feet respectively of the other two. The capacity of the reservoir was 642 million galls. (2910 Ml) and the standard discharge was 18 million gallons per day during working days and 5 mgd at other times. The "safe yield" of the reservoir was only about 11 mgd and it was not unusual for the reservoir to empty completely in a dry summer. It may be noted that this method of operation by no means maximised the benefit to the water power users, since it took no account of the flow in the River Wharfe at the points of use.

A scheme was prepared jointly by Bradford Corporation and the River Authority to reconstruct the reservoir to a capacity of 4,500 mg (20,400 Ml) and use it partly for direct supply and partly for river regulation. The proposed increase of impounded area and the proposed abstractions were covered by licensing, but in view of the complex nature of the scheme and its financing arrangements it was deemed advisable to obtain the other necessary powers by Private Bill. In 1974 the new Regional Water Authority inherited the scheme and amended it to dispense with the direct supply element. They bought out the water power interests in the reservoir of the (by then) two remaining millowners, varied the licences in line with the revised scheme to use the reservoir for regulation only, and proceeded with the scheme.

2.2.2 Additional abstraction from a compensation reservoir

Ponden reservoir on the River Worth, a tributary of the River Aire, is the compensation reservoir for Watersheddles reservoir, a short distance upstream of it. Lower Laithe reservoir in the adjacent valley of Sladen Beck is a combined supply and compensation reservoir. All were in the ownership of the Craven Water Board and Ponden was in the control of the Worth Millowners Committee dominated by one remaining water power user. The Water Board partly bought out the water power user and obtained a licence from the River Authority to abstract 0.5 mgd from the reservoir and to have the compensation discharge fixed as a maintained flow at a weir on the River Worth some two miles downstream of Ponden Dam and below the confluence with Sladen Beck.

2.2.3 Permanent reduction in compensation discharge from a combined supply and compensation reservoir

Warley Moor reservoir of the Calderdale Water Board was required to supply a high proportion (two thirds) of its yield as compensation water and in the late 1960's the Board sought to have this reduced to the more acceptable one third. The reservoir originally fed compensation water to the adjacent Cat-i'-th-Well Brook, a tributary of the River Calder but the water power uses of this stream were, by then, defunct. There remained, however, one water power user on the River Calder who would be affected by the proposal.

The proposal was advertised following the procedure of the Water Resources Act 1963 and submitted to the River Authority. A few objections received by the River Authority could be set aside but the objection from the water power user had to be taken into account since his licence enabled him to put the entire dry weather flows of the Calder through his turbine and any artificial reduction in flow must constitute a derogation. The reduction in flow of some 0.6 mgd with a head of less than 10 feet represented a very small loss in cash value of electrical power but it was necessary to buy out the objection and obtain the power user's agreement to a suitable "downward" variation of his licence before it was possible to vary the compensation provision.

2.2.4 A reduction in compensation discharge including a seasonal variation

Elslack reservoir is a small reservoi[illegible] mg capacity on the Earby Beck, a tributary of the River Aire. [illegible]vily drawn down every summer and the Craven Water Board sought a [illegible]eduction in compensation discharge to a figure of one quarter [illegible]e original. The proposal was duly advertised and the only objection came from the Fisheries Department of the River Authority who valued Earby Beck as a spawning ground for fish. The Fisheries Department accepted that the figure could be reduced to one quarter of the original during the summer but would only accept a reduction of one half during the winter and the River Authority decreed the variation accordingly.

2.2.5 Enlargement of a [illegible]eservoir

The Mid-Calder Water Board decided to construct a new reservoir, Winscar, which would completely drown the Dunford Bridge reservoir and enable an increased yield to be obtained from the catchment. The River Authority took the view that this itself did not call for an increase in compensation discharge and furthermore it agreed to the siting of the compensation gauge some distance downstream of the new dam with some allowance for the additional unreservoired catchment. Objections from angling interests at the time led the Authority in licensing the proposals to make the compensation requirements subject to review after 10 years. Ten years later the review was carried out by the Yorkshire Water Authority in consultation with angling and other interests. No case could be sustained for any alteration in the requirements and they were confirmed without amendment.

2.2.6 Variation in compensation discharge of a compensation water storage reservoir

A paper-making company near Sheffield, drawing some of its water from Morehall Brook a short distance before it flowed into the River Don advertised an application to vary its abstraction licence upwards. Since the abstraction was almost entirely dependent on the compensation water discharged from Morehall reservoir (itself the compensation storage reservoir for Broomhead reservoir), Sheffield Water Undertaking objected to the proposal on the slightly curious grounds that it would make it more difficult for them to obtain a Drought Order should they need one!

The River Authority took this objection at its face value and looked for a solution to the problem. It found that the catchment of Morehall alone was too small to supply the compensation water as a "reliable yield" and they accepted that although the compensation liability extended to Broomhead reservoir, Sheffield Corporation would always apply for a Drought Order rather than discharge compensation water from it deliberately (i.e. other than by overflow). The increased abstraction applied for by the Company was greater than half the compensation discharge and Drought Orders almost always permitted a 50% reduction.

The reservoir records were analysed and long term records of inflow, outflow and storage were derived. It was found possible to draw up a control curve such that if at any time the reservoir level was above that indicated by the curve, the full compensation flow would be discharged and when below the flow would be reduced by one third. The decisions would be made weekly and the flow set for a week.

Wide consultation took place with all river interests including the River Don Millowners Association and angling interests and when the proposals were advertised with the control curve reduced to a weekly table of levels, no objections were received. With the compensation provisions for Broomhead/Morehall reservoirs thus varied, Sheffield Corporation withdrew its objection to the proposed variation of the paper company's licence which was subsequently granted by the River Authority.

This pioneering effort paved the way for the Yorkshire Water Authority to put forward similar amendments to the compensation provisions affecting all the Don reservoirs except Winscar referred to above. The importance of this may be gauged from the fact that 50% of the catchment of the River Don down to Sheffield is reservoired.

APPENDIX A3 RESERVOIR ARCHIVE

TABLE A3.1 LIST AND EXPLANATION OF VARIABLES ON IH RESERVOIR ARCHIVE

RESERVOIR NUMBER — A 6 digit number assigned to each reservoir for reference purposes. The first 3 digits refer to the hydrometric area, and the last 3 to the reservoir number within that area. The fourth digit is used to identify reservoirs which are operated together, either as a chain, with compensation water released from the most downstream, or as a group in order to maintain a fixed flow at some downstream point. All reservoirs in a group or chain have the same number, apart from the fourth digit which denotes the order upstream eg 23202 is upstream of 23102, and both are upstream of 23002 the compensation reservoir.

RESERVOIR NAME

GRID REFERENCE

OPERATOR — *Name of operator abbreviated as shown in Table A3.2*

AUTHORITY — This 2 digit number denotes the Water Authority area in which the reservoir is located. Scotland has been treated as a single area. The numbering system is as follows:

		No.
Scotland	SCOT	1
Northumbrian	NWA	2
Yorkshire	YWA	3
Anglian	AWA	4
Thames	TWA	5
Southern	SWA	6
Wessex	WWA	7
South West	SWWA	8
Welsh	WNWDA	9
Severn Trent	STWA	10
North West	NWWA	11

DATE — Date of impoundment of the reservoir

TYPE — A two digit number code (related to character code) categorising reservoirs according to their current primary function. In some cases this involved a subjective judgement as to which function had the greatest influence on downstream river flows.

1 Hydroelectric with compensation releases downstream of the generating station (A)
5 Hydroelectric with no compensation releases (E)
3 Compensation only (C)
4 Supply and compensation (D)
19 Supply only (S)
16 Pumped storage (P)
18 Regulating (R)

[redacted]ATAREA — The natural catchment area to the dam or maintained flow point (km^2). For a chain of reservoirs the area at each reservoir includes the natural catchments of those upstream.

[redacted]OTAREA — As for NATAREA but also including areas drained by catchwaters. For NWWA and Northern Ireland only, the WA's estimated catchwater efficiency at 80% and reduced the catchwater areas accordingly to be 100% efficient.

[redacted]YIELD — The net yield of the reservoir (in Ml/day). The yield figures are as given by water authorities and are calculated by a range of different methods. These will range from early estimates based on Hawksley's rule and the Lapworth diagram to the results derived from more rigorous probability methods used in recent water resource surveys.
Compensation is deducted from the gross yield to give the net yield or the firm quantity that is available for supply, before consideration of drawoff or treatment capacity. Where a group of reservoirs are operated together, the net yield of the whole system is quoted against the compensation flow.

[redacted]ROSSCAP — The gross capacity of the reservoir (Ml)

[redacted]ETCAP — The net capacity of the reservoir (Ml). This excludes any dead water storage below drawoff points.

[redacted]DFLOW — Natural average flow at the same location as compensation flows, namely the dam site or maintained flow point (in Ml/day). It is estimated using the method outlined in Low Flow Studies Report (NERC, 1980), from average annual rainfall and annual evaporation. Both variables are derived by map analysis - rainfall from 1:250,000 scale map, and potential evaporation (from which actual vaporation is estimated) from 1:2,000,000 scale map.

[redacted]PCODE — The type of release policy is categorised as a number code. Where two release policies operate together it is the policy which has the greatest overall effect on the river which is recorded. For example maintained flows at some downstream point would take precedence over a fixed discharge at the dam. Fuller details of more complex compensation policies such as seasonally varying releases, with freshets or blockgrant allowance are given in the text.

[redacted] = constant discharge from the reservoir 7 days a week
[redacted] = constant discharge 6 days a week
[redacted] = seasonally varying releases
[redacted] = seasonally varying releases plus freshets and/or a block grant allowance
[redacted] = constant discharge, plus freshets or block grant
[redacted] = constant discharge over a variable period eg 6 or 12 hours - An equivalent daily discharge over 7 days is recorded on the archive
[redacted] = constant discharge, which varies weekly or daily according to control rules based on reservoir level and time of year
[redacted] = constant discharge made up from releases from one or more reservoirs
[redacted] = variable discharge, based on estimates of what the natural flow of the river would have been

10–18 = maintained flows:- where a minimum flow has to be maintained at some downstream point, this is denoted by a prefix digit of 1 to the above single digit codes. The second digit indicates the type of discharge pattern which must be maintained (as above).
eg 10 = constant discharge maintained at a downstream point
eg 12=seasonally varying flows maintained at a downstream point

19 = seasonally varying releases at the dam and a constant maintained flow downstream.

COMPFLOW — Compensation flow at the reservoir or maintained flow point (in Ml/day). Reference needs to be made to the type of release policy.

NOTE: NATAREA, TOTAREA, COMPCODE, COMPFLOW, ADFLOW values all relate to the same location - either the dam or maintained flow point.

COMP/ADF — Compensation flow (COMPFLOW) in Ml/day expressed as a proportion of the average flow (ADFLOW) in Ml/day

TABLE A3.2 RESERVOIR OPERATORS

AWA	Anglian Water Authority
BAC	British Aluminium Company
BRWD	Borders Region: Water Department
BSC	British Steel Corporation
BWB	British Waterways Board
BWW	Bristol Waterworks
CEGB	Central Electricity Generating Board
CNDWC	Corby & Northampton District Water Company
CRWD	Central Region: Water Department
CWSD	Central Scotland Water Development Department
EBWC	Eastbourne Water Company
ESWC	East Sussex Water Company
FRWD	Fife region: Water Department
GWPC	Galloway Water and Power Company
HRWD	Highland Region: Water Department
HWC	Hartlepool Water Company
LRWD	Lothian Region: Water Department
MILL	Millowners Committee
NCC	Northampton County Council
NGWC	Newcastle and Gateshead Water Company
NSHEB	North of Scotland Hydro Electric Board
NWA	Northumbrian Water Authority
NWC	Northampton Water Company
NWWA	North West Water Authority
PRIV	Private owner
SRWD	Strathclyde Region: Water Department
SWC	South Staffordshire Water Company
SSWC	Sunderland & South Shields Water Company
STWA	Severn Trent Water Authority
SWA	Southern Water Authority
SWAKWC	Southern Water Authority and Kent Water Company
SWWA	South West Water Authority
TRWD	Tay Region: Water Department
TWA	Thames Water Authority
WDWC	Wrexham and Denbigh Water Company
WNWDA	Welsh National Water Development Authority
WWA	Wessex Water Authority
YWA	Yorkshire Water Authority

TABLE A3.3 LIST OF RESERVOIRS ON I.H. RESERVOIR ARCHIVE

	RESNO	RESERVOIR NAME	GRID REFERENCE	AUTHORITY	OPERATOR
	2001	L BADANLOCH	NC790330	1.	HRWD
	2002	L AN RUATHAIR	NC870355	1.	HRWD
**	3001	L SHIN	NC581051	1.	NSHEB
**	4001	L ACHONOCKIE	NH646545	1.	NSHEB
**	4002	L VAICH	NH345749	1.	NSHEB
**	4003	L GLASCARNOCH	NH345707	1.	NSHEB
	4004	L GARVE	NH422592	1.	NSHEB
**	4005	ORRIN RES	NH403502	1.	NSHEB
**	4006	L GLASS	NH536701	1.	NSHEB
	4007	L MORIE	NH547750	1.	HRWD
**	4201	MEIG RES	NH375560	1.	NSHEB
	4203	L DROMA	NH280745	1.	NSHEB
	4301	L BEANNACHARAIN	NH245508	1.	NSHEB
**	4401	L LUICHART	NH388590	1.	NSHEB
	4501	L FANNICH	NH206560	1.	NSHEB
	4601	L CHROISG		1.	NSHEB
**	5001	L BEINNACHARAN	NH325397	1.	NSHEB
**	5002	L MULLARDOCH	NH222312	1.	NSHEB
**	5003	L BENEVEAN	NH274276	1.	NSHEB
	5004	KILMORACK RES	NH495442	1.	NSHEB
**	5201	L MONAR	NH200390	1.	NSHEB
	5203	L AFFRIC	NH195230	1.	NSHEB
	5204	AIGAS RES	NH474437	1.	NSHEB
**	6001	L DUNDREGGAN	NH357157	1.	NSHEB
**	6002	L GARRY	NH280017	1.	NSHEB
**	6003	L MHOR/FOYERS		1.	NSHEB
	6004	L DUNTELCHAIG	NH647320	1.	HRWD
**	6201	L CLUANIE	NH185097	1.	NSHEB
**	6202	L QUOICH	NH069015	1.	NSHEB
	6301	L LOYNE	NH200050	1.	NSHEB
**	13001	LOCH LEE	NO433801	1.	TRWD
	13002	DEN OF OGIL	NO440619	1.	TRWD
	13003	GLEN OGIL	NO450642	1.	TRWD
	14001	CLATTO	NO361079	1.	
	14002	CAMERON	NO472113	1.	
**	14003	CROMBIE	NO524404	1.	TRWD
**	14004	MONIKIE	NO502380	1.	TRWD
	14005	CLASH	NO349545	1.	TRWD
**	15001	L LINTRATHEN	NO276541	1.	TRWD
**	15002	L BENACHALLY	NO071504	1.	TRWD
**	15003	STRONUICH	NN501420	1.	NSHEB
	15004	L DAIMH	NN509466	1.	NSHEB
**	15005	L LEDNOCK	NN714297	1.	NSHEB
	15006	L EARN	NN642238	1.	NSHEB
	15007	L TAY	NN583354	1.	NSHEB
**	15008	L FASKALLY	NN943578	1.	NSHEB
	15009	L GARRY	NN529706	1.	NSHEB
	15010	L ERICHT	NN553739	1.	NSHEB
	15011	L CUAICH		1.	NSHEB
	15012	L EIGHEACH	NN440570	1.	NSHEB
	15201	BACKWATER	NO253591	1.	TRWD
**	15203	L LYON(LUBREOCH)	NN450423	1.	NSHEB
	15207	LOCHAN NA LAIRIGE	NN255177	1.	NSHEB
**	15208	L TUMMEL	NN915593	1.	NSHEB
	15305	L DUNALASTAIR	NN724591	1.	NSHEB
	15405	L RANNOCH	NN592578	1.	NSHEB
**	15505	L ERROCHTY	NN532942	1.	NSHEB
	16001	GLENFARG	NO105116	1.	FRWD
	16002	L TURRET	NN804254	1.	CWSD
	17001	ARNOT	NO207023	1.	FRWD
	17002	HOLL		1.	FRWD
**	17003	CARRON	NS591839	1.	CRWD
	17004	LOCH COULTER	NS764850	1.	CRWD
	17005	CARRISTON	NO328036	1.	FRWD
	17006	TOUCH SYS	NS735920	1.	CRWD
**	17007	COUL	NO265040	1.	FRWD
	17008	BALGILLIE		1.	FRWD
**	17009	BUCKIEBURN	NS743855	1.	CRWD
	17010	BROADSIDE	NS770832	1.	CRWD
	17011	N THIRD	NS757899	1.	CRWD
**	17013	EARLSBURN 2	NS709835	1.	CRWD
**	17015	FAUGHLIN	NS741831	1.	CRWD
	17017	BO'MAINS	NT020750	1.	CRWD
	17018	MILLHALL		1.	CRWD
	17202	BALLO	NO224050	1.	FRWD
	17210	OVERTON	NS765835	1.	CRWD
	17213	EARLSBURN 1	NS702896	1.	CRWD
	17302	HARPERLEAS SYS	NO212053	1.	FRWD
**	18001	CASTLEHILL	NO003030	1.	FRWD
	18002	DUNBLANE		1.	CRWD
	18003	ARIVURICHARDICH		1.	CRWD
**	18004	L VENACHAR	NN597065	1.	SRWD
**	18005	L ARKLET	NN395096	1.	SRWD
	18006	L LUBNAIG		1.	SRWD
	18007	LOSSBURN		1.	CRWD
	18008	COCKSBURN	NS808987	1.	CRWD
**	18015	GARTMORN	NS935990	1.	CRWD
	18201	GLENSHERRUP RES	NN964044	1.	
	18204	L DRUNKIE	NN549051	1.	SRWD
**	18301	GLENQUAY RES	NN981029	1.	
**	18304	GLEN FINGLAS	NN528077	1.	SRWD
**	18401	GLENDEVON	NN913044	1.	FRWD
	18404	L ACHRAY	NN525064	1.	SRWD
**	18504	L KATRINE	NN623091	1.	SRWD
**	19001	ROSEBERY	NT308568	1.	LRWD
**	19002	EDGELAW	NT304592	1.	LRWD
**	19003	GLENCORSE	NT219639	1.	LRWD
**	19004	PORTMORE	NT260502	1.	LRWD
**	19005	HARPERRIG	NT005610	0.	LRWD

TABLE A3.3 (continued)

	RESNO	RESERVOIR NAME	GRID REFERENCE	AUTHORITY	OPERATOR
	19006	COBBINSHAW	NT017540	1.	BWB
**	19007	FORESTBURN	NS965550	1.	LRWD
**	19008	LOCH COTE	NS985760	1.	CRWD
**	19009	HARLAW	NT065612	1.	LRWD
**	19010	CROSSWOOD	NT057578	1.	LRWD
	19011	TORDUFF	NT206677	1.	LRWD
	19012	N PENTLAND SPR	NT050560	1.	LRWD
	19013	MORTON1	NT075630	1.	LRWD
	19014	MORTON2	NT075637	1.	LRWD
	19015	BONALY	NT211663	1.	LRWD
**	19201	GLADHOUSE	NT290537	1.	LRWD
	19203	LOGANLEA	NT198627	1.	LRWD
	19209	THREIPMUIR	NT176644	1.	LRWD
	19211	CLUBBIEDEAN	NT202659	1.	LRWD
**	20001	HOPES	NT547621	1.	LRWD
	20002	STOBESHIEL	NT500617	1.	LRWD
	20003	THORTERS	NT605695	1.	LRWD
	20004	DONOLLY	NT575694	1.	LRWD
	20005	QUARRELBURN	NT185590	1.	LRWD
	20006	LAMMERLOCH	NT512635	1.	LRWD
**	21001	TALLA	NT118216	1.	LRWD
**	21002	BADDINGSGILL	NT129559	1.	LRWD
**	21003	WEST WATER	NT121524	1.	LRWD
**	21004	ALEMOOR	NT399154	1.	BRWD
**	21005	WATCHWATER	NT664558	1.	BRWD
**	21006	WHITEADDER	NT663633	1.	LRWD
**	21007	FRUID	NT097216	1.	LRWD
	21008	KNOWESDEAN		1.	BRWD
	21009	ACREKNOWE		1.	BRWD
**	21010	MEGGET	NT210230	1.	LRWD
	21208	STANTLING CRAIG		1.	
**	22001	FONTBURN	NZ048937	2.	NWA
**	23001	CATCLEUGH	NT747031	2.	NGWC
	23003	LITTLE SWINBURN	NY947775	2.	NWA
	23004	EAST HALLINGTON	NY960760	2.	NGWC
	23006	WHITTLE DEANSYS	NZ073673	2.	NGWC
**	23007	DERWENT	NZ026513	2.	SSWC
**	23008	SMIDDY SHAW	NZ044464	2.	NWA
	23009	HISHOPE	NZ023465	2.	NWA
**	23010	KIELDER	NY710880	2.	NWA
**	23012	LOCKWOOD	NZ670129	2.	NWA
	23203	COLT CRAG	NY924782	2.	NGWC
	23204	WEST HALLINGTON	NY971761	2.	NGWC
**	24001	BURNHOPE	NY846389	2.	NWA/SSWC
**	24003	TUNSTALL	NZ066407	2.	NWA
	24203	WASKERLEY	NZ025442	2.	NWA
**	25001	CROOKFOOT	NZ429309	2.	HWC
**	25002	HURWORTH BURN	NZ403334	2.	HWC
	25003	HART SYS	NZ482362	2.	NWA
**	25004	GRASSHOLME	NY947228	2.	NWA
**	25005	HURY	NY966196	2.	NWA
**	25009	COW GREEN	NY812290	2.	NWA
	25010	BYERHOPE	NY905464	2.	NWA
	25204	SELSET	NY919211	2.	NWA
	25205	BLACKTON	NY947186	2.	NWA
	25306	BALDERHEAD	NY927193	2.	NWA
**	27001	SCALING	NZ750120	3.	YWA
**	27002	LEIGHTON	SE162798	3.	YWA
**	27003	CODBECK	SE463992	3.	YWA
	27004	OAKDALE LOWER	SE467964	3.	YWA
**	27005	GOUTHWAITE	SE141683	3.	YWA
**	27006	BEAVERDYKE	SE228546	3.	YWA
**	27007	SCARGILL	SE233535	3.	YWA
	27008	TEN ACRES	SE248536	3.	YWA
**	27009	GRIMWITH	SE060643	3.	YWA
	27010	MARCH GHYLL	SE122511	3.	YWA
	27011	CARR BOTTOM	SE147667	3.	YWA
**	27012	LINDLEY WOOD	SE215493	3.	YWA
	27013	ELSLACK	SD936485	3.	YWA
**	27014	EMBSAY	SD995546	3.	YWA
**	27015	SILSDEN	SE045477	3.	YWA
	27016	PONDEN	SD995372	3.	MILL
**	27017	LOWER LAITHE	SE013398	3.	MILL
	27018	LEEMING	SE038343	3.	MILL
**	27019	LEESHAW	SE016353	3.	MILL
	27020	SUNNYVALE	SD210430	3.	MILL
	27021	DOE PARK	SE075343	3.	MILL
	27022	HEWENDEN	SE074356	3.	MILL
	27023	ELDWICK	SE122413	3.	YWA
**	27024	REVA	SE151426	3.	YWA
	27025	WEECHER	SE136421	3.	YWA
	27026	HORSFORTH U+L	SE235402	3.	YWA
**	27027	WIDDOP	SD936328	3.	YWA
**	27028	WARLEY MOOR	SE029317	3.	YWA
**	27029	RYBURN	SE024186	3.	YWA
**	27030	BOOTHWOOD	SE030163	3.	YWA
**	27031	RINGSTONE EDGE	SE051190	3.	YWA
	27032	OGDEN	SE063309	3.	YWA
	27033	HIVENDEN	SE060290	3.	YWA
**	27034	SCAMMONDEN	SE053167	3.	YWA
**	27035	BUTTERLEY	SE046105	3.	MILL
**	27036	DEERHILL	SE070117	3.	YWA
**	27037	BLACKMOORFOOT	SE099130	3.	MILL
	27038	LONGWOOD	SE100173	3.	YWA
**	27039	DIGLEY	SE110070	3.	MILL
**	27040	BROWNHILL	SE117064	3.	YWA
	27041	HOLME STYES	SE140056	3.	MILL
	27042	BOSHAW WHAMS	SE153057	3.	MILL
**	27043	WINSCAR SYS	SE153026	3.	YWA
**	27044	SCOUT DIKE	SE235047	3.	YWA

TABLE A3.3 (continued)

	RESNO	RESERVOIR NAME	GRID REFERENCE	AUTHORITY	OPERATOR
**	27065	DAMFLASK	SK284907	3.	MILL
**	27066	REDMIRES	SK264855	3.	YWA
**	27067	BARDEN	SE012578	3.	YWA
**	27068	CHELKER	SE055515	3.	YWA
**	27069	MORE HALL	SK287958	3.	YWA
**	27050	UNDERBANK	SK253992	3.	YWA
	27051	RIVELIN POND	SK286868	3.	YWA
**	27052	GORPLEY	SD912230	3.	YWA
**	27053	WITHENS CLOUGH	SD990162	3.	YWA
	27054	LUMLEY MOOR	SE222707	3.	YWA
	27055	BOLTBY	SE497986	3.	YWA
	27056	CASTLE CARR	SE023301	3.	YWA
**	27202	POUNDHILL	SE150772	3.	YWA
	27206	OAKDALE UPPER	SE473962	3.	YWA
	27205	SCAR HOUSE	SE058770	3.	YWA
	27206	JOHN O'GAUNTS	SE221546	3.	YWA
	27211	LANSHAW L	SE141649	3.	YWA
	27212	SWINSTY	SE198525	3.	YWA
	27216	WATERSHEDDLES	SD969380	3.	MILL
	27221	STUBDEN	SE062332	3.	MILL
	27223	GRAINCLIFFE	SE118421	3.	YWA
**	27227	WALSHAW DEAN U+L	SD959329	3.	YWA
	27228	DEAN HEAD U+L	SE022307	3.	YWA
	27229	BAITINGS	SE010159	3.	YWA
	27230	BOOTH DEAN SYS	SE011151	3.	YWA
	27236	DEAN HEAD	SE038152	3.	YWA
	27235	BLAKELEY	SE054096	3.	MILL
	27239	BILBERRY	SE103070	3.	MILL
	27240	RAMSDEN	SE114056	3.	YWA
	27243	LWR WINDLEDON	SE158019	3.	YWA
	27244	ROYD MOOR	SE222048	3.	YWA
	27245	AGDEN	SK261923	3.	YWA
	27249	BROOM HEAD	SK269959	3.	YWA
	27250	MIDHOPE	SK223996	3.	YWA
	27251	RIVELIN SYS	SK271868	3.	MILL
	27305	ANGRAM	SE040760	3.	YWA
	27312	FEWSTON	SE187541	3.	YWA
	27316	KEIGHLEY MOOR	SD989394	3.	YWA
**	27327	GORPLE U+L	SD940314	3.	YWA
	27330	GREEN WITHENS	SD990162	3.	YWA
	27335	WESSENDEN	SE058087	3.	MILL
	27340	RIDING WOOD	SE116052	3.	YWA
	27343	HARDEN	SE152037	3.	YWA
	27344	INGBIRCHWORTH	SE215060	3.	YWA
	27345	DALE DIKE	SK243917	3.	YWA
	27350	LANGSETT	SE214002	3.	YWA
	27412	THRUSCROSS	SE152578	3.	YWA
	27435	WESSENDEN HEAD	SE068076	3.	MILL
	27440	YATEHOLME	SE112047	3.	YWA
	27443	SNAILSDEN	SE136040	3.	YWA
	27445	STRINES	SK232905	3.	YWA
**	28001	BLACKBROOK	SK460170	10.	STWA
**	28002	RUDYARD	SJ945596	10.	BWB
**	28003	TITTESWORTH	SJ991590	10.	STWA
	28004	SULBY	SP654811	10.	BWB
	28005	BARBROOK	SK279771	10.	STWA
	28006	BELVIDE	SJ864102	10.	BWB
**	28007	LADYBOWER	SK199854	10.	STWA
	28008	NANPANTAN	SK507170	10.	STWA
	28009	RAMSLEY		10.	STWA
**	28010	CROPSTON	SK545109	10.	STWA
	28012	STAUNTON HAROLD	SK375230	10.	
**	28013	THORNTON	SK473075	10.	STWA
**	28014	BLITHFIELD	SK060245	10.	SWC
	28015	KNIPTON	SK830331	10.	BWB
**	28016	OGSTON	SK366604	10.	STWA
	28207	DERWENT	SK173898	10.	STWA
	28210	SWITHLAND	SK560140	10.	
	28307	HOWDEN	SK170924	10.	STWA
	29001	COVENHAM	SK365965	4.	AWA
	29002	TOFT NEWTON	SK045880	4.	AWA
	29003	CADNEY		4.	AWA
	30001	DENTON	SK880330	4.	BWB
	30002	REVESBY	SK320675	4.	PRIV
	31001	SADDINGTON	SP670915	4.	BWB
	31002	EYE BROOK	SP860960	4.	CNDWC
**	31003	EMPINGHAM/RUTLD	SK940040	4.	AWA
**	32001	RAVENSTHORPE	SP680702	4.	AWA
**	32002	HOLLOWELL	SP690720	4.	AWA
	32003	DAVENTRY	SP580630	4.	AWA
**	32004	PITSFORD	SP760685	4.	AWA
	32005	SYWELL	SP835665	4.	NCC
**	32006	THORPE MALSOR	SP825790	4.	NWC
**	32007	CRANSLEY	SP825790	4.	NWC
**	33001	FOXCOTE	SP710365	4.	AWA
**	33002	GRAFHAM	TL140645	4.	AWA
	34001	ORMSBY BROAD	TG450110	4.	AWA
	34002	FRITTON LAKE	TG480000	4.	AWA
**	36001	ALTON	TM160350	4.	AWA
	37001	LEIGHS	TL710185	4.	AWA
**	37002	ABBERTON	TL980185	4.	AWA
**	37003	HANNINGFIELD	TQ715985	4.	AWA
**	37004	ARDLEIGH	TM035275	4.	AWA
**	40001	WEIR WOOD	TQ407353	5.	SWA
**	40002	BEWL BRIDGE	TQ680330	6.	SWA
**	40003	BROAD OAK	TR160620	5.	SWAKWC
**	40004	BOUGH BEECH	TQ496480	5.	ESWC
**	40005	DARWELL	TQ715212	5.	SWA
**	40006	POWDERMILL	TQ800195	6.	SWA
	41001	ARLINGTON	TQ534074	6.	ESWC

TABLE A3.3 (continued)

	RESNO	RESERVOIR NAME	GRID REFERENCE	AUTHORITY	OPERATOR
**	41002	ARDINGLY	TQ330293	6.	SWA
	43001	NUTSCALE	SS863434	7.	WWA
**	45001	WIMBLEBALL	SS965293	8.	SWWA
**	46001	AVON	SX679651	8.	SWWA
**	46002	FERNWORTHY	SX670843	8.	SWWA
**	46003	TRENCHFORD	SX806523	8.	SWWA
**	46005	VENFORD	SX686711	8.	SWWA
	46203	TOTTIFORD	SX810827	8.	SWWA
	46303	KENNICK	SX807838	8.	SWWA
**	47001	BURRATOR	SX551690	8.	SWWA
**	47003	UPPER TAMAR	SS291115	8.	SWWA
**	48001	COLLIFORD	SX179710	8.	SWWA
**	48002	DRIFT	SW437285	8.	SWWA
**	48003	SIBLYBACK	SX232702	8.	SWWA
**	48004	STITHIANS	SW719363	8.	SWWA
**	49001	CROWDY	SX140833	8.	SWWA
**	49002	PORTH	SW864622	8.	SWWA
**	50001	MELDON	SX563917	8.	SWWA
**	50002	WISTLAN POUND	SS563414	8.	SWWA
**	52002	CLATWORTHY	ST044312	7.	WWA
	52005	ASHFORD	ST237386	7.	WWA
**	52006	DURLEIGH	ST274363	7.	WWA
**	52007	BLAGDON	ST505[illegible]	7.	BWW
	52008	LUXHAY	ST20317[illegible]	7.	WWA
	52009	CHEDDAR	ST4605[illegible]	7.	BWW
	52010	BLACKDOWN HILLS	ST2231[illegible]	7.	WWA
**	52011	SUTTON BINGHAM	ST556115	7.	WWA
**	52205	HAWKRIDGE	ST212364	7.	WWA
	53001	MONKSWOOD	ST757712	7.	WWA
	53002	CHEW VALLEY	ST572615	7.	WWA
	53003	CHEW MAGNA		7.	
	53202	SHERBORNE	ST586550	7.	BWW
**	54001	STANFORD	SP597803	10.	
	54002	CLYWEDOG	SN912870	10.	STWA
**	54003	VYRNWY	SJ012202	10.	STWA
	54005	NASEBY	SP669777	10.	BWB
	54006	CHELMARSH	SN733876	10.	SWC
	54007	TRIMPLEY	SN770799	10.	
	54008	DRAYCOTE WATER	SP454701	10.	STWA
**	55001	CARAN COCH	SN910643	9.	WNWDA
	55201	GARREG DDU	SN909650	9.	WNWDA
	55301	PEN Y GARREG	SN902674	9.	WNWDA
	55401	CRAIG GOCH	SN897700	9.	WNWDA
	55501	CLAERWEN	SN847653	9.	WNWDA
	55601	DOL Y MYNACH	SN905615	9.	WNWDA
**	56001	GRWYNE	SO230329	9.	WNWDA
**	56002	USK	SN820287	9.	WNWDA
**	56003	CRAY	SN882215	9.	WNWDA
**	56004	TALYBONT	SO1001[illegible]	9.	WNWDA
**	56005	LLANDEGFEDD	ST33099[illegible]	9.	WNWDA
	56006	CWMTILLERY	SO220070	9.	WNWDA
**	56007	CARNO	SO164131	9.	WNWDA
**	56009	LLYN Y FAN FACH	SN803218	9.	WNWDA
	56010	PANTYREOS	ST257916	9.	WNWDA
**	56011	WENTWOOD	ST430930	9.	WNWDA
	56207	LLANGYNIDR	SO153141	9.	WNWDA
**	57001	LLWYN-ON	SO007121	9.	WNWDA
**	57002	TAF FECHAN	SO061119	9.	WNWDA
**	57003	PENDERYN	SN950071	9.	WNWDA
	57004	LLANISHEN	ST187817	9.	WNWDA
**	57005	LLUESTWEN	SN950016	9.	WNWDA
	57006	NANT MOEL	SN981070	9.	WNWDA
	57007	LISVANE	ST189821	9.	WNWDA
	57201	CANTREF	SN994159	9.	WNWDA
	57202	NEUADD LOWER	SO030180	9.	WNWDA
	57301	BEACONS	SN987182	9.	WNWDA
	57302	NEUADD UPPER	SO030188	9.	WNWDA
**	58001	YSTRADFELLTE	SN945175	9.	WNWDA
	58002	CWM WERNDERI	SS810903	9.	WNWDA
	58003	EGLWYSNUNYDD	SS795847	9.	BSC
**	58004	LLYN FAWR	SN919032	9.	WNWDA
**	59001	LLIW RES LOWER	SN650035	9.	WNWDA
**	59002	LLIEDI LOWER	SN518039	9.	WNWDA
	59201	LLIW RES UPPER	SN662064	9.	WNWDA
	59202	LLIEDI UPPER	SN512046	9.	WNWDA
**	60001	LLYN BRIANNE	SN805502	9.	WNWDA
**	61001	LLYS Y FRAN	SN036255	9.	WNWDA
**	61201	PRESCELLY	SN065295	9.	WNWDA
	62001	LLYN EGNANT	SN793671	9.	WNWDA
	62002	TEIFI	SN754576	9.	WNWDA
	63001	NANT Y MOCH	SN760870	9.	CEGB
	63002	CWM RHEIDOL	SN700793	9.	CEGB
	63003	DINAS	SN748822	9.	CEGB
	63004	LLYN LLYGAD RHEIDOL	SN792877	9.	WNWDA
	64001	LLYN BODLYN	SH647240	9.	WNWDA
	64002	CYNWYCH LLYN	SH738278	9.	WNWDA
	64003	CRAIG Y PISTYLL	SN722857	9.	WNWDA
	65001	LLYN LLYDAW	SH629543	9.	CEGB
**	65002	LLYN CWELLYN	SH560550	9.	WNWDA
**	65003	CWMYSTRADLLYN	SH563445	9.	WNWDA
	65004	LLYN CWMDULYN	SH496495	9.	WNWDA
	65005	LLYN MORWYNION	SH740420	9.	WNWDA
	65006	TECWYN UCHAF	SH[illegible]	9.	WNWDA
	65007	TRAWSFYNYDD	SH[illegible]	9.	CEGB
	65008	TAN Y GRISIAU	SH683447	9.	WNWDA
	66001	LLYN COWLYD	SH727626	9.	WNWDA
	66002	LLYN CRAFNANT	SH7[illegible]	9.	WNWDA
**	66003	ALED ISAF	SH913596	9.	WNWDA
	66004	LLYN CONWY	SH780460	9.	WNWDA
	66005	LLYN ELSI	SH783552	9.	WNWDA

[illegible] 3.3 (continued)

	RESNO.	RESERVOIR NAME	GRID REFERENCE	AUTHORITY	OPERATOR
	65036	[illegible]NNON LL[illegible]	SH593627	3.	CEGB
	66037	LAKE DULYN	SH703655	4.	UNHOS
	66038	PL[illegible]S UCHAF	SH269710	9.	WNWDA
	66203	LLYN ALED	SH[illegible]570	9.	WNWDA
	67031	AL[illegible]EN	SH255528	9.	WNWDA
	67032	LLYN CELYN	SH970404	9.	WNWDA
**	67033	[illegible]RENIG	SH830560	9.	WNWDA
	67004	LLYN ARENIG	[illegible]	9.	WNWDA
	67035	LLYN TEGID (BALA)		9.	
	67036	C[illegible]THAY LLYN	[illegible]	9.	WDWC
	67037	P[illegible]DIVAS	[illegible]235518	9.	WDWC
**	67038	T[illegible] MAWR	SJ275480	9.	WDWC
**	69031	SPRING HILL	SD870170	11.	NWWA
**	69033	H[illegible]DEN WOOD(HASLINGDEN SYS)	SD750220	11.	NWWA
**	69034	NEW YEARS BRIDGE([illegible]HAM SYS)	SD990120	11.	NWWA
**	69035	DELPH	SD700160	11.	NWWA
**	69036	L STRINESDALE(STRINESDALE SYS)	SD760360	11.	NWWA
	69037	B[illegible]SHES CL.	SD950090	11.	NWWA
**	69038	GREENBOOTH(NADEN)	SD860160	11.	NWWA
**	69010	[illegible]KERWOOD(SWINESHAW SYS)	SJ010990	11.	NWWA
**	69011	DOWESTONE(ASHTON SYS)	SK010030	11.	NWWA
**	69012	CLO[illegible]N/BUTTON	SD950270	11.	NWWA
	69013	GREENFOLD	SD9222[illegible]2	11.	NWWA
**	69014	C[illegible]E SYS	SD940200	11.	NWWA
	69015	[illegible]TY MOOR	SD930190	11.	NWWA
	69016	[illegible]EPHOUSES SYS	SD[illegible]80220	11.	NWWA
	690[illegible]	[illegible]BLES(ENTWHISTLE SYS)	SD730[illegible]0	11.	NWWA
**	69019	[illegible]GLE SPRINGS(SPRINGS SYS)	SD[illegible]901[illegible]	11.	NWWA
**	69020	[illegible]M RID	SD670100	11.	NWWA
	69021	[illegible]WORTH	SD[illegible]	11.	NWWA
**	69022	CL[illegible]WBRIDGE	SD[illegible]	11.	NWWA
**	69023	BELMONT	SD670170	11.	NWWA
**	69027	BOTTOMS+TEGGS NOSE(LANGLEY SYS)	[illegible]	11.	NWWA
**	69028	LAMALOAD	[illegible]	11.	NWWA
**	69029	BOTTOMS(LONGDENDALE)	SK[illegible]0990	11.	NWWA
	69030	SWINESHAW (SWINESHAW SYS)	SK0[illegible]0850	11.	NWWA
	69031	[illegible]ST	SD[illegible]	11.	NWWA
**	69032	DE[illegible]ILDE(TOTT SYS)	SK010750	11.	NWWA
**	69033	[illegible]DEN(PIETHORNE SYS)	SD951120	11.	NWWA
**	69034	[illegible]	SD[illegible]C0190	11.	NWWA
	69035	[illegible]BS	SJ040790	11.	BWB
	69036	[illegible]ON	SD790090	11.	BWB
**	69038	[illegible]RGROVE	SD910190	11.	NWWA
**	69039	[illegible]ADER	SK050990	11.	NWWA
**	69041	[illegible]LESHAW SYS	SD990100	11.	NWWA
	69042	[illegible]DEN	SD920210	11.	NWWA
**	69044	[illegible]LINGHURST(CLAYME PARK SYS)	SJ970830	11.	NWWA
**	69045	[illegible]WORTH	SD930157	11.	NWWA
**	69047	[illegible]TON	SD736163	11.	NWWA
	70031	[illegible]LANDS	SD550120	11.	NWWA
**	70032	WORTHINGTON(WORTHINGTON SYS)	SD560110	11.	NWWA
**	70034	RIVINGTON(RIVINGTON SYS)	[illegible]30125	11.	NWWA
	71031	LUPTON	SD580540	11.	NWWA
**	71032	STOCKS	SD730550	11.	NWWA
**	71003	EARNSDALE(SUNNYHURST SYS)	SD670220	11.	NWWA
**	71034	OGDEN SYS(U+L)	SD820400	11.	NWWA
**	71036	HURSTWOOD	SD836316	11.	NWWA
**	71037	CHURN CLOUGH	SD780380	11.	NWWA
**	71038	MITCHELLS SYS	SD790270	11.	NWWA
**	71039	COLDWELL SYS	SD900350	11.	NWWA
**	71011	CANT CLOUGH	SD894308	11.	NWWA
	71012	LEA GREEN(SWINDEN SYS)	SD879339	11.	NWWA
	71015	LANESHAW	SD950410	11.	NWWA
	71016	WALVERDEN	SD873370	11.	NWWA
	71017	HODDLESDEN	SD720[illegible]0	11.	NWWA
**	71018	ELA CROSS U+L	SD530610	11.	NWWA
**	72032	GRIZEDALE(BARNACRE SYS)	[illegible]530450	11.	NWWA
	73031	TARNHOUSE	SD573534	11.	NWWA
	73032	FISHER TARN	SD550930	11.	NWWA
	73003	BIRDS PARK SYS	SD540920	11.	NWWA
	73034	DUBBS	NY420020	11.	NWWA
	73005	BORRANS	NY430010	11.	NWWA
	73036	GHYLL HEAD	SD400920	11.	NWWA
	73007	SIMPSON GRND(SIMPSON SYS)	SD390950	11.	NWWA
**	73038	LEVERS WATER	SD282990	11.	NWWA
	73039	PICKUP BANK SYS	SD720240	11.	NWWA
**	73010	DEAN CLOUGH SYS	SD710330	11.	NWWA
	73011	KENTMERE	NY440070	11.	PRIV.
	73012	KILLINGTON	SD[illegible]0930	11.	BWB
**	74001	ENNERDALE	NY[illegible]0150	11.	NWWA
**	74032	POAKA BECK(POAKA BECK SYS)	SD240790	11.	NWWA
	74003	BAYSTON BANK	SD[illegible]70590	11.	NWWA
**	74034	SEATHWAITE TARN	[illegible]10930	11.	NWWA
**	74035	PENNINGTON	SD2[illegible]757	11.	NWWA
**	75031	CRUMMOCK WATER	NY150210	11.	NWWA
	75032	CHAPEL HOUSE(CHAPEL HSE SYS)	NY260360	11.	NWWA
**	75033	THIRLMERE	NY310150	11.	NWWA
**	76031	HAWESWATER	NY[illegible]0140	11.	NWWA
	76032	HAYESWATER	NY430120	11.	NWWA
**	76033	CASTLECARROCK	NY[illegible]0550	11.	NWWA
**	76034	WET SLEDDALE	NY550110	11.	NWWA
**	77031	BLACK ESK	NY[illegible]968	1.	
	77032	WINTERHOPE	NY279826	1.	
**	79031	AFTON	NS[illegible]3502	1.	SRWC
	79002	KETTLETON	NS[illegible]09001	1.	
	80031	LOCHINVAR	NX659853	1.	
**	80032	GLENKILN	[illegible]845780	1.	
**	80033	TONGLAND	NX702565	1.	GWPC
	80034	L DOON	NS476016	1.	GWPC
	80203	LOCH KEN	NX732646	1.	GWPC

TABLE A3.3 (continued)

	RESNO	RESERVOIR NAME	GRID REFERENCE	AUTHORITY	OPERATOR
	80303	EARLSTOUN	NX614923	1.	GWPC
	80403	CARSFAD	NX606856	1.	GWPC
	80503	KENDOON	NX614892	1.	GWPC
	80603	CLATTERINGSHAWS	NX546753	1.	GWPC
	81001	DINDINNIE	NX025595	1.	
**	81002	PENWHIRN	NX129595	1.	
**	82001	BRADAN	NX635977	1.	SRWD
**	82002	CRAIGENDUNTON	NS523454	1.	SRWD
**	82003	PECAWR	NX660937	1.	SRWD
**	83002	CAMPHILL	NS273556	1.	SRWD
	83003	KELLY	NS223693	1.	SRWD
**	83004	CAAF	NS254609	1.	SRWD
	83005	MUNNOCH	NS255478	1.	SRWD
	83006	LOCH GOIN	NS534473	1.	SRWD
	83008	BENNAN	NS524505	1.	SRWD
	83009	L CRAIG	NS528509	1.	SRWD
	83010	DUNWAN	NS555495	1.	SRWD
	83011	PICKETLAW	NS[illegible]8519	1.	SRWD
	83202	MUIRHEAD	NS260563	1.	SRWD
	83204	KNOCKENDON	NS244519	1.	SRWD
	84001	W CORRIE		1.	CRWD
	84002	WOODBURN		1.	CRWD
	84003	E CORRIE		1.	CRWD
**	84006	DAER	NS981091	1.	SRWD
**	84007	CAMPS	NT001224	1.	SRWD
	84008	ROWBANK/BARCRAIGS	NS392572	1.	SRWD
	84009	BURNCROOKS	NS483706	1.	SRWD
**	84010	GRYFE NOS1+2	NS287716	1.	SRWD
	84012	STANELY	NS469613	1.	SRWD
	85002	L LOMOND		1.	CWSD
**	86001	L SLOY	NN290115	1.	NSHEB
**	86002	L SHIRA	NN160190	1.	NSHEB
**	86003	ALLT NA LAIRIGE	NN275130	1.	NSHEB
	86004	L TARSAN	NS070833	1.	NSHEB
	87001	L GLASHAN	NR920925	1.	NSHEB
**	88001	TRALAIG RES	NM970150	1.	NSHEB
	88002	SREINGE RES	NR864145	1.	NSHEB
**	89001	L NANT	NN000255	1.	NSHEB
**	89002	L AWE	NN979045	1.	NSHEB
	89202	CRUACHAN	NN092275	1.	NSHEB
	90001	BLACKWATER RES	NN246603	1.	BAC
	91001	L LOCHY	NN182945	1.	NSHEB
**	91002	L LAGGAN	NN440830	1.	BAC
**	91003	L TREIG	NN340775	1.	BAC
**	93001	L MORAR	NM583923	1.	NSHEB
	94001	L BAD AN SGALAIG	NG948720	1.	NSHEB
	95001	L ASSYNT	NC167250	1.	NRWD
	95002	L DUBH	NC149012	1.	NSHEB
	97001	L MORE	ND085460	1.	NRWD
**	97002	L CALDER	ND085596	1.	NRWD

	RESNO.	RESERVOIR NAME	GRID REFERENCE	AUTHORITY	OPERATOR
**	102001	ALAW	SH390365	9.	WNWDA
**	102002	CEFNI	SH440770	9.	WNWDA
**	104001	GLEN LUSSA	NR707255	1.	
	105001	STORR LOCHS SYS	NG510525	1.	NSHEB

NOTE Reservoir numbers are prefixed by 'R' in the text to avoid confusion with W.D.U. gauging station numbers

** Subset of reservoirs analysed in detail in Chapter 3.

TABLE A3.4 I.H. RESERVOIR ARCHIVE

	RESNO	TYPE	DATE	NYIELD	GROSSCAP	NETCAP	NATAREA	TOTAREA	ADFLOW	COMPCODE	COMPFLOW	COMP/ADF
	2001	18.	----	----	----	----	----	----	----	----	----	----
	2002	16.	----	----	----	----	----	----	----	----	----	----
**	3001	1.	----	----	21800.	----	491.00	----	1744.87	3.	90.[illegible]	0.051
**	4001	1.	----	----	----	----	626.20	626.18	2550.00	10.	545.52	0.214
**	4002	1.	----	----	11213.	----	[illegible]	90.[illegible]	778.05	7.	36.37	0.047
**	4003	1.	----	----	78155.	----	99.33	14[illegible].13	778.05	7.	36.37	0.[illegible]
	4004	5.	----	----	----	----	----	----	----	----	----	----
**	4005	1.	----	----	59[illegible].	----	118.51	136.18	----	3.	45.46	----
**	4006	18.	----	----	----	----	103.80	[illegible].30	340.[illegible]	10.	27.30	0.080
	4007	----	1978.	----	----	----	----	----	----	----	----	----
**	4201	1.	----	----	----	----	177.34	177.34	----	3.	90.92	----
	4301	5.	----	----	----	----	----	----	----	----	----	----
**	44[illegible]	1.	1926.	----	168910.	----	389.28	[illegible].33	----	3.	90.[illegible]	----
	4501	1.	1930.	----	376618.	----	[illegible].39	13[illegible].77	----	----	----	----
**	5001	1.	----	----	----	----	285.97	----	1409.50	14.	5[illegible]5.50	0.387
**	5002	1.	----	----	193378.	----	127.68	127.68	----	0.	2.[illegible]	----
**	5003	1.	----	----	27467.	----	273.00	294.44	1618.50	2.	190.93	0.118
	5004	----	----	----	----	----	----	----	----	10.	1136.50	----
**	5201	1.	----	----	141564.	----	170.50	----	998.60	14.	136.38	0.137
	5203	5.	----	----	----	----	122.70	122.79	----	0.	0.00	----
	5204	----	----	----	----	----	----	----	----	10.	1136.50	----
**	6001	1.	----	----	----	----	336.00	----	1768.61	3.	102.28	0.0[illegible]
**	6002	1.	----	----	----	----	361.41	361.41	2028.80	13.	68.20	0.034
**	6003	26.	----	----	13600.	----	----	207.20	----	0.	0.00	----
**	6201	1.	----	----	203032.	----	175.50	----	1206.80	14.	454.46	0.377
**	6202	1.	----	----	353909.	----	131.10	134.11	1041.21	4.	90.92	0.084

TABLE A3.4 (continued)

	RESNO	TYPE	DATE	NYIELD	GROSSCAP	NETCAP	NATAREA	TOTAREA	ADFLOW	COMPCODE	COMPFLOW	COMP/ADF
	6301	1.	----	----	43035.	----	64.72	68.74	----	----	----	----
**	13001	4.	1950.	15.45	2250.	----	57.25	----	196.75	4.	29.55	0.151
	13002	4.	----	4.51	605.	----	2.48	----	3.68	0.	0.91	0.247
	13003	4.	----	7.96	270.	----	18.57	----	42.94	0.	4.55	0.106
**	14003	4.	1868.	2.27	890.	----	5.80	----	7.07	0.	0.82	0.116
**	14004	4.	1853.	3.41	2035.	----	----	----	----	0.	0.47	----
	14005	19.	----	1.82	23.	----	----	----	----	----	----	----
**	15001	4.	1873.	61.37	9730.	----	72.83	72.83	----	0.	18.41	----
**	15002	4.	----	----	2520.	----	8.09	----	15.56	2.	3.41	0.219
**	15003	1.	----	----	----	----	97.07	186.22	628.40	13.	163.66	0.260
	15004	----	----	----	42758.	----	----	----	----	----	----	----
**	15005	1.	----	----	30073.	----	59.56	----	207.25	12.	27.28	0.132
	15006	1.	----	----	----	----	----	----	----	----	----	----
**	15008	1.	----	----	----	----	1829.60	----	6141.40	10.	1136.50	0.185
	15009	----	----	----	38313.	----	----	----	----	----	----	----
	15010	----	----	----	229367.	----	----	----	----	----	----	----
	15011	5.	----	----	----	----	----	----	----	----	----	----
	15012	1.	----	----	10194.	----	236.82	----	1078.00	19.	1818.40	1.687
	15201	19.	1969.	40.91	25003.	----	34.39	34.39	----	0.	0.00	----
**	15203	1.	----	----	82968.	----	69.31	140.84	----	13.	----	----
	15207	----	----	----	13204.	----	----	986.79	----	----	----	----
**	15208	1.	----	----	36359.	----	----	----	----	3.	181.84	----
	15308	5.	----	----	----	----	----	----	----	----	----	----
	15408	5.	----	----	46150.	----	----	----	----	----	----	----
**	15508	1.	----	----	32480.	----	91.75	----	245.80	13.	68.19	0.277
	16001	----	----	20.46	----	----	----	----	----	----	----	----

TABLE A3 — 4 (continued)

	RESNO	TYPE	DATE	NYIELD	GROSSCAP	NETCAP	NATAREA	TOTAREA	FLOW	COMPCODE	COMPFLOW	COMP/ADF
	16002	1.	----	----	18100.	----	----	----	----	----	----	----
	17001	1.	----	----	----	----	2.62	----	4.41	0.	1.73	0.393
	17002	1.	----	----	----	----	----	----	----	----	----	----
**	17003	4.	1939.	90.00	19525.	----	39.63	----	133.45	4.	----	----
	17004	4.	1823.	7.55	3790.	----	1.81	3.60	4.60	0.	5.55	1.206
	17005	4.	----	3.40	----	----	3.44	----	3.48	0.	0.43	0.123
	17006	4.	1896.	1.89	----	----	0.45	4.00	1.27	0.	1.30	1.024
**	17007	4.	----	----	----	----	5.56	----	6.69	0.	0.86	0.129
	17008	4.	----	----	----	----	----	----	----	0.	0.17	----
**	17009	4.	1905.	4.63	875.	----	----	9.70	----	0.	2.19	----
	17010	19.	1890.	4.32	99.	----	----	0.20	----	0.	0.00	----
	17011	4.	1911.	----	----	----	----	----	----	----	----	----
**	17013	4.	1901.	4.09	595.	----	4.83	4.83	15.47	0.	4.18	0.270
**	17015	19.	1890.	8.49	1363.	----	----	4.00	----	0.	0.00	----
	17017	----	1900.	----	73.	----	----	----	----	----	----	----
	17018	----	1905.	----	86.	----	----	----	----	----	----	----
	17202	4.	----	----	----	----	3.88	----	5.83	0.	4.32	0.742
	17210	19.	----	----	50.	----	----	----	----	0.	0.00	----
	17213	4.	1895.	4.32	632.	----	2.37	2.30	----	0.	0.00	----
	17302	4.	----	----	----	----	2.75	----	4.52	0.	1.73	0.383
**	18001	4.	1979.	----	----	----	61.50	----	212.15	4.	----	----
	18002	----	1933.	----	114.	----	----	----	----	----	----	----
	18003	----	1934.	----	----	----	----	----	----	----	----	----
**	18004	3.	1859.	405.50	11770.	----	211.76	211.76	----	0.	224.12	----
**	18005	4.	1914.	69.10	12283.	----	18.01	18.01	----	0.	1.36	----
	18007	----	1897.	1.80	173.	----	----	----	----	0.	0.55	----

TABLE A3.4 (continued)

	RISNO	TYPE	DATE	NYIELD	GROSSCAP	NETCAP	NATAREA	TOT[illegible]	ADFLOW	COMPCODE	COMPFLOW	COMP/ADF
**	18008	19.	1667.	[illegible].66	179.	----	----	1.60	----	0.	0.00	----
**	18015	19.	1700.	6.60	1996.	----	----	----	----	0.	----	----
	18204	3.	----	----	3519.	----	----	----	----	----	----	----
**	18301	4.	----	6.80	----	----	5.06	----	17.01	0.	3.41	0.2[illegible]
**	18304	4.	1965.	81.83	19093.	----	39.11	39.11	----	0.	45.46	----
**	18401	4.	----	67.50	----	----	23.30	----	83.50	0.	29.20	0.350
	18404	4.	----	----	----	----	----	----	----	----	----	----
**	18504	4.	1859.	343.22	64611.	----	[illegible].85	93.85	----	0.	22.73	----
**	19001	3.	1880.	42.30	1728.	----	34.44	----	52.18	0.	5.46	0.105
**	19002	3.	1880.	0.00	1299.	----	28.56	----	36.85	0.	6.27	0.17[illegible]
**	19003	4.	1822.	2.27	1673.	----	14.62	----	25.24	0.	9.09	0.360
**	19004	4.	1079.	3.18	1164.	----	2.87	----	5.50	0.	0.39	0.071
**	19005	3.	1859.	0.00	4091.	----	16.87	----	31.43	0.	15.91	0.5[illegible]
	19006	----	----	----	----	----	----	----	536.00	----	----	----
**	19007	19.	1865.	4.50	1050.	----	----	----	----	----	0.00	----
**	19008	19.	1900.	2.55	912.	----	----	----	----	----	0.00	----
**	19009	3.	1848.	----	727.	----	18.56	----	33.97	0.	12.27	0.361
	19010	3.	1860.	0.00	796.	----	8.20	----	15.19	0.	3.41	0.225
	19011	----	1851.	17.70	----	----	----	----	----	----	----	----
	19012	----	1864.	17.70	----	----	----	----	----	----	----	----
	19013	19.	1885.	2.73	36.	----	----	----	----	0.	0.00	----
	19014	19.	1893.	----	400.	----	----	----	----	0.	0.00	----
	19015	4.	1853.	0.09	200.	----	----	----	----	0.	0.82	----
**	19201	4.	1879.	42.30	8133.	----	27.00	----	42.98	0.	7.72	0.180
	19205	----	1851.	2.27	532.	----	----	----	----	----	----	----
	19209	3.	1847.	0.00	2359.	----	----	----	----	0.	0.00	----

TABLE A3.4 (continued)

	RESNO	TYPE	DATE	NYIELD	GROSSCAP	NETCAP	NATAREA	TOTAREA	ADFLOW	COMPCODE	COMPFLOW	COMP/ADF
	19211	3.	1950.	0.91	255.	----	----	----	----	----	0.00	----
**	20001	4.	1935.	4.40	1410.	----	5.22	----	9.36	0.	1.36	0.145
	20002	4.	1911.	1.40	246.	----	----	----	----	0.	0.36	----
	20003	4.	1900.	2.45	336.	----	----	----	----	0.	0.68	----
	20004	4.	[illegible]	1.50	275.	----	----	----	----	0.	0.64	----
	20005	4.	[illegible]	0.32	71.	----	----	----	----	0.	0.16	----
	20006	4.	[illegible]	[illegible]	127.	----	----	----	----	0.	1.14	----
**	21001	4.	1905.	75.00	12020.	----	24.00	24.80	89.90	2.	0.00	0.000
**	21002	4.	1930.	12.27	2210.	----	9.25	9.25	21.07	3.	4.02	0.191
**	21003	4.	1965.	----	2344.	----	----	6.68	13.64	3.	2.86	0.210
**	21004	4.	1962.	9.09	----	----	23.19	----	62.71	0.	4.55	0.073
**	21005	4.	1950.	8.20	----	----	----	10.70	15.89	0.	2.27	0.143
**	21006	4.	1969.	29.55	7956.	----	----	45.60	66.59	3.	6.79	0.102
**	21007	4.	1966.	43.20	10910.	----	20.60	20.60	72.74	3.	17.96	0.247
	21008	19.	----	----	----	----	----	----	----	----	----	----
	21009	19.	1900.	----	----	----	----	----	----	0.	0.00	----
**	21010	4.	1982.	102.50	61400.	----	----	40.00	163.66	3.	27.28	0.167
	21208	3.	1881.	----	----	----	----	----	----	0.	3.18	----
**	22001	4.	1907.	15.90	----	3280.	30.29	30.29	45.15	0.	2.30	0.051
**	23002	4.	1905.	45.50	----	10479.	39.88	39.88	92.87	0.	13.60	0.146
	23003	4.	1890.	13.20	----	155.	17.73	17.73	18.75	----	----	
	23004	4.	1871.	----	----	3120.	12.81	----	12.39	----	----	----
	23006	16.	1857.	13.60	----	2459.	----	51.52	----	----	----	----
**	23007	4.	1966.	112.70	----	50007.	87.20	110.16	132.83	3.	23.87	0.180
**	23008	4.	1877.	----	----	1350.	----	9.66	13.42	----	0.00	0.000

TABLE A3.4 (continued)

	RESNO	TYPE	DATE	HYDYELD	GROSSCAP	NETCAP	NATAREA	TOTAREA	ADFLOW	COMPCODE	COMPFLOW	COMP/ADF
**	23010	18.	1980.	----	----	201000.	237.9[illegible]	----	585.74	2.	114.00	0.195
**	23012	4.	1977.	----	----	520.	2.23	4.74	----	0.	0.00	----
	23203	19.	[illegible]	----	----	4855.	16.03	16.03	----	----	----	----
	23204	19.	18[illegible]9.	----	----	3380.	----	----	----	----	----	----
**	24001	4.	1937.	36.8[illegible]	----	6169.	19.56	42.81	60.29	0.	9.10	0.151
**	24003	4.	1879.	15.90	----	236[illegible].	25.43	----	36.23	0.	5.60	0.155
	24205	19.	1872.	----	----	2046.	5.37	----	8.23	----	----	----
**	25001	6.	1903.	----	----	1059.	----	5.40	----	0.	0.00	----
**	25002	6.	1871.	----	----	727.	----	13.90	----	0.	0.0[illegible]	----
	25005	4.	1858.	----	----	[illegible]00.	----	2.70	----	----	----	----
**	[illegible]	4.	1915.	134.[illegible]	----	6060.	78.67	78.67	22[illegible].59	0.	28.40	0.126
**	25006	4.	1896.	----	----	3904.	43.12	43.12	[illegible]0.14	0.	15.22	0.169
**	[illegible]909	18.	1971.	159.10	----	[illegible]	[illegible]	58.96	2[illegible].53	0.	33.60	0.145
	[illegible]	6.	----	----	----	----	----	----	----	0.	0.00	----
	25204	19.	1960.	----	----	[illegible]	70.62	----	217.[illegible]	----	----	----
	25206	19.	18[illegible].	23[illegible].80	----	[illegible]	----	----	91.39	----	----	----
	25306	[illegible]	1965.	----	----	19[illegible]70.	21.31	----	47.12	----	----	----
**	27001	[illegible]	----	----	----	1682.	5.87	5.87	4.78	0.	0.68	0.142
**	27002	[illegible]	1929.	[illegible].64	----	4775.	21.77	21.77	33.18	[illegible]	9.2[illegible]	0.271
**	2700[illegible]	[illegible]	19[illegible].	4.09	----	51[illegible].	7.61	7.61	7.30	----	0.0[illegible]	0.000
	27[illegible]		1840.	[illegible].00	----	67.	5.06	5.06	4.[illegible]5	0.	0.76	0.1[illegible]4
**	27005	3.	1901.	[illegible].60	----	7118.	1[illegible].40	----	2[illegible].64	6.	89.[illegible]	0.349
**	27006	6.	18[illegible].	----	----	[illegible].	[illegible].75	----	5.02	0.	0.30	0.059
**	27007	[illegible]	[illegible]	----	----	7[illegible].	[illegible].75	----	4.[illegible]8	0.	0.[illegible]	0.130
	27008	6.	18[illegible]	----	[illegible]	[illegible]47.	----	1.66	----	0.	0.04	----
**	27009	[illegible]	[illegible]	----	----	22200.	2[illegible].0[illegible]	25.83	60.01	0.	23.[illegible]	0.798

TABLE A3.4 (continued)

RESNO	TYPE	DATE	NYIELD	GROSSCAP	NETCAP	NATAREA	TOTAREA	ADJAREA	COMPCODE	COMPFLOW	COMP/ADF
27010	4.	1906.	1.81	----	376.	----	[illegible]	----	0.	0.60	----
27011	4.	1904.	0.67	----	76.	----	1.69	----	0.	0.10	----
** 27012	3.	1875.	59.00	----	3046.	[illegible]	----	118.76	0.	18.20	0.153
27013	4.	1932.	0.20	----	232.	----	1.86	----	2.	----	----
** 27014	4.	1907.	1.80	----	797.	[illegible]	2.69	3.36	0.	1.19	0.352
** 27015	3.	1862.	0.00	----	650.	8.10	8.10	9.45	[illegible]	6.14	0.650
27016	4.	1877.	5.90	----	231.	20.70	----	49.51	11.	8.75	0.177
** 27017	4.	1926.	5.90	----	1318.	4.37	4.37	10.40	15.	2.08	0.197
27018	3.	1877.	0.00	----	[illegible]	[illegible]	2.09	[illegible]	0.	----	----
** 27019	3.	1879.	0.00	----	400.	2.04	2.04	[illegible]	0.	--	----
27020	3.	----	----	----	----	----	----	----	----	----	----
[illegible]	3.	1862	0.00	----	486.	[illegible]	----	11.70	0.	[illegible]	0.350
27022	3.	1843.	0.00	----	242.	----	3.96	----	0.	----	----
27023	3.	1860.	0.00	----	123.	[illegible]	[illegible]	5.45	[illegible]	1.00	0.183
** 27024	4.	1894.	0.61	----	544.	2.91	2.91	2.69	0.	0.79	0.299
27025	4.	1892.	0.10	----	148.	----	1.86	----	0.	[illegible]	----
27026	4.	1861.	1.58	----	72.	1.58	1.58	----	0.	0.21	----
** 27027	4.	1878.	34.00	----	2880.	34.00	----	87.28	10.	20.00	0.229
** 27028	4.	1872.	6.04	----	741.	5.85	5.85	11.30	0.	3.02	0.267
** 27029	4.	1933.	16.60	----	949.	[illegible]	----	15.02	0.	5.91	0.393
** 27030	4.	1971.	22.15	----	3637.	15.62	15.62	34.02	0.	9.66	0.284
** 27031	4.	----	21.15	----	1040.	----	----	----	----	0.00	----
27032	4.	1888.	0.92	----	990.	4.21	----	7.78	0.	----	----
27033	3.	1873.	4.92	----	478.	----	----	----	0.	8.33	----
** 27034	4.	1970.	28.51	----	7873.	6.26	22.26	[illegible]	0.	12.27	0.819
** 27035	4.	1907.	4.27	----	1773.	14.40	----	35.94	0.	8.07	0.225

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TABLE A3.4 (continued)

	RESNO	TYPE	DATE	NYIELD	GROSSCAP	NETCAP	NATAREA	TOTAREA	ADFLOW	COMPCODE	COMPFLOW	COMP/ADF
##	27036	4.	1875.	4.46	----	736.	1.19	3.79	2.84	0.	[illegible]	0.493
##	27037	4.	1876.	14.67	----	3091.	1.44	8.19	3.24	0.	[illegible]	1.012
	27038	3.	1828.	----	----	160.	----	----	----	0.	----	----
##	27039	4.	1953.	12.10	----	3342.	9.07	9.07	26.32	4.	6.49	0.247
##	27040	4.	1928.	12.05	----	1185.	9.60	----	[illegible]	0.	6.82	0.216
	27041	4.	1838.	2.06	----	300.	----	2.19	[illegible]	[illegible]	0.89	----
	27042	3.	1840.	----	----	200.	----	0.86	----	[illegible]	1.27	----
##	27043	4.	1975.	18.66	----	8296.	12.35	----	34.80	12.	10.46	0.301
##	27044	3.	192[illegible].	11.91	----	709.	12.50	----	21.82	[illegible]	[illegible]	0.177
##	27045	3.	1896.	22.50	----	5037.	43.40	----	71.10	[illegible]	36.40	0.512
##	27046	19.	1836.	12.86	----	1423.	4.30	10.41	6.99	0.	0.00	0.000
##	27047	19.	1882.	22.14	----	4357.	14.16	14.16	27.39	0.	0.00	0.000
##	27048	19.	1866.	4.10	----	1036.	5.22	5.22	----	0.	0.00	----
##	27049	3.	1930.	24.25	----	2028.	26.29	26.29	44.58	6.	12.02	0.270
##	27050	3.	1907.	39.00	----	2727.	38.72	38.72	69.59	6.	21.00	0.302
	27051	3.	1869.	6.20	----	18.	7.60	----	18.22	0.	2.27	0.125
##	27052	4.	1905.	2.46	----	598.	2.84	2.84	[illegible]	0.	1.33	0.171
##	27053	4.	1894.	6.59	----	1330.	4.19	----	[illegible]	0.	2.64	0.289
	27054	4.	1888.	2.27	----	360.	----	2.95	[illegible]	0.	0.45	----
	27055	19.	1882.	0.91	----	116.	----	----	----	----	----	----
	27056	----	1872.	6.04	----	12.	----	----	----	----	----	----
##	27202	4.	1916.	7.75	----	2364.	11.70	11.70	18.56	0.	4.55	0.245
	27204	19.	1914.	----	----	----	2.59	2.59	----	----	----	----
	27205	19.	1936.	85.50	----	10069.	----	----	----	----	----	----
	27206	3.	1890.	6.85	----	555.	----	----	3.07	----	----	----
	27211	19.	1855.	----	----	----	----	----	----	----	----	----

TABLE A3.4 (cont[illegible])

	RESNO	TYPE	DATE	NYIELD	GROSSCAP	NETCAP	NATAREA	TOTAREA	ADFLOW	COMPCODE	COMPFLOW	COMP/ADF
	27212	19.	1876.	90.00	----	3937.	----	68.99	----	----	----	----
	27216	19.	1878.	----	----	----	----	6.47	----	----	----	----
	27221	19.	1868.	----	----	----	----	5.27	----	----	----	----
	27223	19.	1885.	----	----	----	----	4.53	----	----	----	----
***	27227	4.	1907.	34.20	----	715.	----	9.41	----	10.	----	----
	27228	4.	1872.	6.04	----	535.	----	----	----	----	----	----
	27229	19.	1958.	----	----	----	----	----	----	----	----	----
	27230	19.	1923.	22.15	----	48.	----	----	----	----	----	----
	27234	19.	1840.	28.51	----	436.	----	----	----	----	----	----
	27235	19.	1903.	----	----	----	----	----	----	----	----	----
	27239	19.	1838.	----	----	----	----	----	----	----	----	----
	27240	19.	1892.	----	----	----	----	----	----	----	----	----
	27243	4.	1872.	18.66	----	357.	----	2.78	----	12.	----	----
	27244	19.	1934.	11.91	----	832.	----	----	----	0.	0.00	----
	27245	19.	1869.	22.80	----	2541.	----	28.24	----	----	----	----
	27249	19.	1934.	24.25	----	4919.	21.96	21.96	----	----	----	----
	27250	19.	1903.	39.00	----	----	----	26.68	----	----	----	----
	27251	19.	1848.	6.20	----	61[illegible].	----	----	----	----	----	----
	27308	19.	1913.	85.80	----	[illegible]	----	----	----	----	----	----
	27312	19.	1879.	90.00	----	[illegible]	----	52.71	----	----	----	----
	27316	4.	1846.	5.90	----	33[illegible].	----	1.57	----	11.	----	----
***	27327	4.	1934.	34.20	----	1253.	8.06	8.06	----	10.	----	----
	27330	19.	1924.	27.15	----	2356.	----	----	----	----	----	----
	27335	19.	1839.	----	----	----	----	----	----	----	----	----
	27340	19.	1878.	----	----	----	----	----	----	----	----	----
	27343	19.	1899.	18.66	----	348.	----	2.04	----	12.	----	----

TABLE A3.4 (continued)

	RESID	TYPE	DATE	NYIELD	GROSSCAP	NETCAP	NATAREA	TOTAREA	ADFLOW	COMPCODE	COMPFLOW	COMP/ADF
	27344	19.	1868.	11.91	----	1332.	----	----	----	----	----	----
	27345	19.	1875.	22.50	----	2118.	----	16.10	----	----	----	----
	27350	19.	1905.	39.00	----	5901.	----	21.10	----	----	----	----
	27412	19.	1961.	90.00	----	7842.	----	28.81	----	----	----	----
	27435	19.	1881.	----	----	----	----	----	----	----	----	----
	27440	19.	1878.	----	----	----	----	----	----	----	----	----
	27443	19.	1899.	18.66	----	176.	----	0.84	----	----	----	----
	27445	19.	1869.	22.50	----	2059.	----	11.69	----	----	----	----
**	28001	16.	----	6.80	----	2300.	10.86	----	8.24	0.	0.33	0.040
**	28002	----	----	----	----	----	10.25	----	13.93	0.	0.91	0.065
**	28003	4.	----	----	6376.	----	27.13	----	43.04	0.	14.77	0.343
	28006	19.	1912.	2.05	----	421.	----	4.18	----	0.	0.00	----
**	28007	18.	1945.	----	----	28685.	126.26	126.26	335.89	0.	136.40	0.406
	28008	19.	1870.	0.91	132.	45.	----	1.73	----	0.	0.00	----
	28009	19.	1902.	0.50	----	82.	----	0.53	----	0.	0.00	----
**	28010	19.	1870.	15.91	----	2528.	----	17.81	----	0.	0.00	----
	28012	16.	----	----	----	----	----	----	----	----	----	----
**	28013	19.	1884.	4.55	1473.	1441.	----	11.57	----	0.	0.00	----
**	28014	4.	1953.	72.74	----	18184.	115.69	----	109.75	0.	22.73	0.208
**	28016	16.	----	----	6180.	----	31.50	----	34.52	0.	5.91	0.171
	28207	19.	1916.	----	----	9638.	----	----	----	----	----	----
	28210	----	1894.	----	----	2220.	----	14.16	----	0.	0.00	----
	28307	19.	1912.	----	----	9001.	----	----	----	----	----	----
	29001	16.	1968.	64.00	10910.	----	----	----	----	----	----	----
	29002	16.	1974.	----	761.	----	----	----	----	----	----	----
	29003	15.	1974.	----	900.	----	----	----	----	----	----	----

TABLE A3.4 (continued)

	RESNO	TYPE	DATE	NYIELD	GROSSCAP	NETCAP	NATAREA	TOTAREA	ADFLOW	COMPCODE	COMPFLOW	COMP/ADF
	30001	19.	----	----	----	----	11.75	----	5.70	----	----	----
	30002	19.	----	----	----	----	----	----	----	----	----	----
	31001	19.	----	----	----	----	10.50	----	6.01	----	----	----
	31002	4.	1940.	13.64	8096.	----	60.70	----	33.59	0.	3.18	0.095
**	31003	16.	1977.	295.00	12400.	----	75.10	----	----	0.	4.55	----
**	32001	4.	1888.	----	1900.	----	11.61	----	6.77	1.	0.45	0.066
**	32002	4.	1938.	----	2000.	----	10.10	----	6.25	1.	0.45	0.072
	32003	4.	----	----	----	----	9.31	----	5.66	----	----	----
**	32004	16.	1954.	35.00	17500.	----	48.60	----	22.90	2.	2.73	0.119
	32005	19.	1950.	----	----	----	----	----	----	----	----	----
**	32006	4.	1905.	----	600.	----	5.38	----	2.62	0.	0.09	0.034
**	32007	4.	1886.	----	700.	----	7.30	----	3.44	0.	0.45	0.131
**	33001	19.	1954.	7.00	600.	----	3.06	----	1.48	----	0.00	0.000
**	33002	16.	1966.	183.00	56856.	----	15.58	----	4.49	2.	----	----
	34001	----	----	5.00	1400.	----	36.44	----	15.87	----	----	----
	34002	----	----	8.00	800.	----	29.31	----	11.64	----	----	----
**	36001	16.	1981.	33.00	6000.	----	20.00	----	----	0.	0.91	----
	37001	18.	1967.	----	----	----	29.69	----	16.67	----	----	----
**	37002	16.	1945.	----	23200.	----	43.31	----	8.31	2.	----	----
**	37003	16.	1956.	----	26100.	----	13.80	----	4.12	0.	1.00	0.243
**	37004	16.	1970.	23.19	2400.	----	13.50	----	3.48	14.	----	----
**	40001	4.	1954.	14.10	----	5623.	26.00	26.90	23.79	2.	4.55	0.191
**	40002	16.	1976.	76.00	----	31367.	19.80	19.80	----	0.	3.40	----
**	40003	16.	1984.	93.00	----	20000.	----	----	----	0.	1.80	----
**	40004	16.	1971.	22.70	----	8630.	----	----	----	2.	0.20	----
**	40005	16.	1950.	21.90	----	4460.	9.60	9.60	[illegible].26	2.	0.55	0.059

TABLE A3.4 (continued)

	RESNO	TYPE	DATE	NYIELD	GROSSCAP	NETCAP	NATAREA	TOTAREA	ADFLOW	COMPCODE	COMPFLOW	COMP/ADF
**	40006	4.	1933.	----	----	856.	----	----	----	0.	2.10	----
	41001	16.	1970.	3750.00	----	----	----	0.00	----	0.	16.30	----
**	41002	16.	1978.	----	----	----	22.00	22.00	19.89	10.	0.80	0.040
	43001	4.	1941.	----	178.	----	5.50	----	18.53	6.	1.40	0.076
**	45001	18.	1979.	83.10	21840.	21320.	29.10	----	67.04	4.	9.10	0.136
**	46001	4.	1956.	9.32	1378.	1291.	13.10	----	56.85	4.	5.91	0.104
**	46002	18.	1942.	23.87	1727.	[illegible]	9.30	----	37.93	0.	5.68	0.150
**	46005	19.	1907.	----	----	686.	9.19	----	16.41	----	0.00	0.000
**	46005	3.	1907.	8.18	864.	773.	2.74	----	11.14	0.	1.82	0.163
	46203	19.	1861.	----	----	377.	----	----	----	----	0.00	----
	46303	19.	1884.	----	----	791.	----	----	----	----	0.00	----
**	47001	16.	1898.	----	4660.	4210.	21.70	----	80.01	0.	2.62	0.033
**	47003	4.	1975.	8.20	1364.	1335.	12.60	----	26.69	0.	2.70	0.101
**	48001	18.	1983.	----	----	25410.	12.40	----	42.15	4.	5.68	0.135
**	48002	4.	1961.	12.30	----	1310.	19.00	----	35.34	0.	1.40	0.040
**	48003	18.	1968.	----	3360.	3180.	8.00	----	26.87	0.	3.09	0.115
**	48004	16.	1965.	20.90	5410.	5205.	8.79	----	20.82	0.	2.70	0.130
**	49001	4.	1973.	6.18	----	1041.	4.17	----	14.17	0.	1.40	0.099
**	49002	4.	1960.	9.60	----	514.	24.70	----	37.93	0.	1.59	0.042
**	50001	4.	1972.	19.09	3090.	3020.	16.60	----	90.72	0.	7.73	0.085
**	50002	4.	1956.	12.73	----	1550.	3.42	----	11.14	0.	0.68	0.06[illegible]
**	52002	4.	1960.	19.00	5363.	----	17.88	----	35.51	0.	4.55	0.128
	52005	[illegible]	1934.	10.10	50.	----	14.26	----	14.61	7.	1.14	0.078
**	52006	4.	1937.	----	959.	----	17.19	----	15.78	0.	1.14	0.072
**	52007	4.	1902.	----	8456.	----	24.50	----	39.20	2.	8.64	0.220
	52008	4.	----	----	----	----	1.06	----	1.4[illegible]	2.	----	----

TABLE A3.4 (continued)

	RESNO	TYPE	DATE	NYIELD	GROSSCAP	NETCAP	NATAREA	TOTAREA	ADFLOW	COMPCODE	COMPFLOW	COMP/ADF
	52009	19.	1938.	----	6137.	----	0.00	----	----	----	----	----
	52010	4.	1938.	----	----	----	----	----	----	7.	0.45	----
**	52011	4.	1955.	----	2455.	----	31.88	----	34.24	0.	2.27	0.066
**	52205	4.	1962.	----	864.	----	21.06	----	11.85	0.	0.68	0.057
	53001	4.	----	----	237.	----	1.56	----	1.71	0.	0.86	0.503
	53002	4.	----	----	20457.	----	57.40	----	73.[illegible]	----	----	----
	53003	3.	----	----	114.	----	----	----	----	2.	----	----
	53202	4.	----	----	----	----	----	----	----	0.	4.28	----
**	54001	4.	----	----	1530.	----	53.56	----	32.58	0.	4.55	0.140
	54002	18.	1968.	----	50006.	----	49.00	49.00	179.35	10.	850.00	4.739
**	54003	18.	1891.	207.30	59700.	55148.	73.90	94.25	309.98	8.	22.70	0.073
	54006	----	----	----	----	----	----	22.70	----	----	----	----
	54007	16.	----	----	----	----	----	----	----	----	----	----
	54008	----	1969.	----	22700.	----	----	----	----	----	----	----
**	55001	18.	1904.	340.90	55536.	----	----	182.10	657.30	0.	118.20	0.180
	55[illegible]1	18.	1904.	----	----	----	----	----	----	----	----	----
	5[illegible]301	18.	1904.	----	6058.	----	----	----	----	----	----	----
	55401	18.	1904.	----	921[illegible].	----	----	----	----	----	----	----
	55501	18.	1952.	----	49006.	----	----	----	----	----	----	----
	55601	18.	1904.	----	602.	----	----	----	----	----	----	----
**	56001	[illegible]	1928.	6.[illegible]	1532.	----	5.85	5.85	17.30	0.	3.41	0.197
**	56002	18.	1955.	32.95	12271.	----	13.[illegible]	15.80	57.30	0.	[illegible]	0.151
**	56003	18.	1907.	18.26	4575.	----	8.87	10.89	53.60	0.	6.82	0.127
**	56004	4.	1959.	60.00	11670.	----	24.09	30.15	98.76	2.	25.00	0.253
**	56005	18.	1963.	184.50	25945.	----	6.07	----	13.80	0.	2.50	0.181
	[illegible]	4.	[illegible]	2.05	[illegible]	----	2.63	2.63	6.76	0.	1.36	0.201

TABLE A3.4 (continued)

	RESNO	TYPE	DATE	NYIELD	GROSSCAP	NETCAP	NATAREA	TOTAREA	ADFLOW	COMPCODE	COMPFLOW	COMP/ADF
**	56007	4.	1909.	3.20	800.	----	6.34	6.34	[illegible]	0.	0.95	0.080
**	56009	4.	1919.	6.36	909.	----	2.17	2.17	16.00	2.	2.07	0.129
	56010	4.	[illegible]	2.27	659.	----	----	2.56	----	----	----	----
**	56011	4.	[illegible]	4.45	1864.	----	----	8.84	15.60	0.	1.36	0.087
	56207	19.	1879.	1.91	----	----	4.52	4.52	4.33	----	[illegible]	0.000
**	57001	4.	1927.	58.20	5505.	----	43.00	43.00	170.00	7.	23.20	[illegible]
**	57002	4.	1927.	86.40	16200.	----	33.80	33.80	138.00	7.	21.80	[illegible]
**	57003	4.	1910.	----	600.	----	0.60	----	13.30	----	----	----
	57004	19.	[illegible]	----	1441.	----	0.00	----	----	----	----	----
**	57005	4.	1892.	9.10	1100.	----	6.01	6.01	48.40	----	0.00	0.000
	57006	4.	1898.	3.25	318.	----	2.12	2.12	7.30	0.	0.33	0.045
	57007	----	----	----	----	----	3.30	----	----	----	----	----
	57201	19.	1892.	----	1491.	----	----	----	75.20	----	----	----
	57202	19.	1884.	18.20	195.	----	8.14	8.14	----	----	0.00	----
	57301	19.	1897.	----	1578.	----	----	----	35.40	----	----	----
	57302	19.	1902.	----	1364.	----	5.74	5.74	25.90	----	0.00	0.000
**	58001	4.	1914.	16.60	3182.	----	9.60	9.60	41.80	0.	7.63	0.183
	58002	----	1902.	2.23	218.	----	----	3.12	----	----	----	----
	58003	----	----	----	3600.	----	----	----	----	----	----	----
**	58004	4.	1914.	----	909.	----	0.60	----	27.80	0.	0.80	0.029
**	59001	16.	1978.	8.41	1137.	----	----	----	----	0.	4.20	----
**	59002	4.	1879.	15.45	818.	----	----	16.29	27.60	0.	0.00	0.000
	59201	19.	1894.	----	1137.	----	----	----	----	----	----	----
	59202	19.	1902.	----	818.	----	----	11.46	12.10	----	----	----
**	60001	18.	1972.	----	61007.	----	----	88.00	342.10	16.	----	----
**	61001	18.	1972.	----	9110.	----	28.00	28.00	82.10	0.	13.60	0.166

TABLE A3.4 (continued)

	RESNO	TYPE	DATE	NYIELD	GROSSCAP	NETCAP	NATAREA	TOTAREA	ADFLOW	COMPCODE	COMPFLOW	COMP/ADF
***	61201	4.	1932.	12.27	641.	----	8.49	----	33.80	0.	1.82	0.054
	62001	4.	1965.	2.27	523.	----	----	0.85	0.35	4.	0.25	0.714
	62002	4.	1960.	3.55	705.	----	----	1.58	0.25	4.	0.55	2.200
	63001	----	1962.	----	32549.	----	----	----	----	----	----	----
	63002	----	----	----	682.	----	----	----	----	----	----	----
	63003	----	----	----	991.	----	----	----	----	----	----	----
	63004	4.	1880.	2.50	295.	----	0.77	0.77	7.30	----	----	----
	64001	4.	1894.	3.77	468.	----	3.80	3.80	18.90	0.	2.18	0.115
	64002	4.	1960.	1.41	273.	----	0.38	0.38	1.76	----	----	----
	64003	4.	1938.	3.45	350.	----	5.06	5.06	20.40	0.	1.82	0.089
***	65002	18.	1976.	15.91	1547.	----	----	20.10	141.40	16.	----	----
***	65003	18.	1958.	8.15	2028.	----	4.90	4.90	25.40	6.	5.91	0.233
	65004	4.	1896.	----	246.	----	2.31	2.31	13.20	0.	2.70	0.205
	65005	----	1897.	----	441.	----	----	----	4.50	----	----	----
	65006	----	1938.	1.91	432.	----	0.40	1.00	1.28	----	----	----
	65007	----	----	----	32549.	----	----	----	----	----	----	----
	66001	4.	1920.	135.00	12502.	----	----	36.10	177.00	----	----	----
	66002	----	1879.	8.00	455.	----	5.67	5.67	29.50	----	----	----
***	66003	18.	1939.	15.00	1227.	----	10.93	10.93	25.90	6.	2.27	0.088
	66004	4.	1964.	2.60	364.	----	1.40	1.40	7.70	0.	0.90	0.117
	66005	----	1912.	----	227.	----	----	0.90	1.40	----	----	----
***	66006	4.	----	3.40	1420.	----	3.70	3.70	18.10	0.	4.50	0.249
	66007	4.	----	13.60	----	----	2.99	2.99	14.10	0.	1.64	0.116
	66008	----	1870.	2.05	227.	----	3.64	3.44	----	----	----	----
	66203	18.	193[illegible].	----	1705.	----	1.62	1.62	----	----	----	----
***	67001	4.	1916.	35.40	14529.	11837.	25.50	25.50	63.07	2.	10.23	0.162

TABLE A3.4 (continued)

	RESNO	TYPE	DATE	NYIELD	GROSSCAP	NETCAP	NATAREA	TOTAREA	ADFLOW	COMPCODE	COMPFLOW	COMP/ADF
	67002	18.	1965.	----	81000.	----	----	70.00	267.84	----	----	----
**	67003	18.	1976.	330.00	61500.	----	22.00	22.00	53.57	2.	6.82	0.127
	67004	----	1888.	9.10	1623.	----	1.45	1.45	6.91	----	----	----
	67005	18.	1952.	----	18000.	----	----	262.00	993.60	----	----	----
	67006	----	1892.	0.28	296.	----	0.19	0.19	----	----	0.00	----
	67007	----	1895.	1.50	282.	----	2.47	2.47	----	7.	0.57	----
**	67008	4.	1905.	3.30	591.	----	----	6.47	----	7.	0.32	----
**	69001	4.	1887.	2.00	605.	545.	2.26	2.26	5.80	0.	1.57	0.271
**	69003	4.	1841.	9.90	2474.	2227.	8.61	11.80	24.37	0.	5.84	0.240
**	69004	4.	1880.	6.90	1720.	1548.	5.46	5.46	13.60	0.	2.48	0.182
**	69005	4.	----	----	[illegible]	2194.	5.12	5.12	13.90	0.	2.20	0.158
**	69006	4.	1832.	4.50	[illegible]	702.	2.55	3.56	5.01	0.	0.04	0.008
	69007	4.	1859.	0.00	227.	204.	1.99	1.99	4.60	0.	1.96	0.426
**	69008	4.	1846.	14.70	4411.	4248.	8.02	11.84	19.10	0.	6.36	0.333
**	69010	4.	1864.	5.00	2176.	1958.	5.44	5.44	11.40	0.	3.64	0.319
**	69011	4.	1876.	21.40	6443.	5800.	19.95	19.95	57.40	0.	15.90	0.277
**	69012	4.	1897.	3.30	872.	785.	1.37	2.45	6.00	0.	1.09	0.182
	69013	4.	1860.	1.10	300.	270.	1.09	1.19	2.63	0.	0.68	0.259
**	69014	4.	1911.	2.70	630.	567.	2.51	2.51	7.70	0.	1.50	0.195
	69015	4.	1910.	0.90	217.	195.	1.00	1.00	2.80	0.	0.62	0.221
	69016	4.	1853.	0.60	138.	102.	1.55	2.13	4.15	0.	0.86	0.207
**	69017	4.	1971.	52.00	10617.	9555.	34.39	34.39	94.20	0.	20.03	0.21[illegible]
**	69019	19.	1830.	4.60	850.	765.	0.00	2.34	0.00	0.	0.00	----
**	69020	19.	1892.	1.20	550.	495.	0.00	0.74	0.00	0.	0.00	----
	69021	3.	1849.	----	432.	389.	2.76	2.76	5.20	0.	5.20	1.000
**	69022	4.	1866.	4.50	1468.	1321.	4.05	4.59	10.70	0.	3.15	0.294

TABLE A3.4 (continued)

	RESNO	TYPE	DATE	NUMFIELD	GROSSCAP	NETCAP	NATAREA	TOTAREA	ADFLOW	COMPCODE	COMPFLOW	COMP/ADF
***	69023	3.	1826.	----	1886.	1699.	7.06	7.06	19.60	0.	15.63	0.797
***	69027	3.	1850.	4.40	1401.	1121.	6.28	7.03	8.84	0.	2.39	0.270
***	69028	4.	1964.	4.90	1909.	1718.	12.40	13.09	15.00	10.	3.32	0.210
***	69029	3.	1849.	112.00	23813.	20978.	78.10	78.10	315.70	10.	68.19	0.216
	69030	4.	1860.	1.80	281.	253.	2.45	2.45	5.80	0.	0.86	0.148
	69031	4.	1838.	2.00	167.	150.	5.06	5.06	13.40	0.	1.14	0.085
***	69032	4.	1937.	32.80	9294.	8608.	21.18	21.18	66.70	10.	13.64	0.204
***	69033	4.	1866.	8.40	4164.	3748.	6.25	7.50	14.17	0.	4.56	0.322
***	69034	4.	1877.	6.00	----	1085.	----	3.10	9.20	0.	0.31	0.034
***	69038	4.	1938.	12.60	3273.	2946.	6.33	7.48	12.00	0.	2.86	0.238
***	69039	4.	1912.	13.50	2343.	1992.	8.95	8.95	26.40	[illegible]	1.10	0.042
***	69041	4.	1891.	5.00	1771.	1594.	3.65	3.85	9.60	0.	2.27	0.236
	69043	4.	1882.	2.20	473.	426.	1.94	2.03	5.73	0.	0.98	0.171
***	69044	4.	1861.	4.70	716.	614.	2.93	5.62	[illegible]	0.	0.00	0.000
***	69217	4.	----	----	----	----	13.39	13.39	9.90	0.	2.45	0.247
	70001	4.	1907.	0.80	168.	[illegible]	0.51	0.51	[illegible]	0.	0.00	0.000
***	70002	19.	1867.	6.50	1046.	941.	0.36	7.86	[illegible]	0.	0.00	0.000
***	70004	4.	1847.	48.50	----	17270.	----	39.60	----	7.	25.75	----
	71001	4.	----	0.60	41.	39.	0.97	0.97	2.30	0.	0.00	0.000
***	71002	4.	1932.	50.00	----	13568.	----	37.50	125.30	3.	13.64	0.109
***	71003	4.	----	1.80	757.	647.	0.21	0.21	5.00	5.	1.80	0.360
***	71004	19.	1894.	----	930.	837.	4.45	4.45	12.70	0.	0.00	0.000
***	71006	4.	----	----	1373.	----	2.40	[illegible]	2.92	0.	[illegible]	0.459
***	71007	4.	1892.	[illegible]	[illegible]	565.	1.35	1.74	3.26	7.	1.62	0.497
***	71009	4.	1855.	1.80	857.	771.	1.75	1.75	4.00	0.	1.23	[illegible]
***	71010	4.	1818.	1.70	549.	494.	1.62	1.62	3.40	0.	0.91	0.268

TABLE A3.4 (continued)

	RESNO	TYPE	DATE	NYIELD	GROSSCAP	NETCAP	NATAREA	TOTAREA	ADFLOW	COMPCODE	COMPFLOW	COMP/ADF
**	71011	4.	----	----	1137.	----	4.25	4.25	9.61	0.	2.29	0.238
	71012	4.	----	----	100.	----	3.99	3.99	8.10	0.	2.56	0.316
	71015	4.	1889.	1.70	341.	307.	2.99	2.99	6.50	5.	1.10	0.169
	71016	3.	1869.	----	92.	83.	7.49	7.49	[illegible]	5.	0.66	0.043
	71017	3.	1849.	----	282.	254.	5.01	5.01	[illegible]	[illegible]	6.00	0.465
**	71018	4.	----	----	500.	450.	3.64	3.64	9.30	0.	3.56	[illegible]
**	72002	4.	1866.	22.00	----	2268.	----	10.30	29.60	0.	0.00	0.000
	73001	4.	1925.	1.70	235.	223.	0.24	1.32	0.56	0.	0.00	0.000
	73002	4.	----	1.90	419.	377.	0.64	1.05	1.82	0.	0.27	0.148
	73003	4.	1848.	0.70	92.	83.	0.36	0.70	0.92	0.	0.00	0.000
	73004	19.	1883.	1.40	115.	104.	0.83	1.52	2.89	0.	0.00	0.000
	73005	3.	1883.	----	82.	74.	1.32	1.32	4.50	0.	0.45	0.100
	73006	19.	1914.	0.90	103.	93.	0.56	0.74	1.63	0.	0.00	0.000
	73007	4.	1957.	1.90	355.	332.	1.62	1.62	4.20	0.	0.20	0.047
**	73008	4.	----	5.50	1114.	1114.	1.90	1.90	12.40	0.	2.00	0.161
	73009	4.	1849.	3.10	493.	428.	2.17	2.17	5.50	0.	0.00	0.000
**	73010	4.	1869.	2.10	1091.	982.	1.38	1.88	2.06	0.	0.00	0.000
	73011	----	----	11.00	----	909.	5.40	5.40	28.64	----	----	----
	73012	18.	----	----	3480.	----	----	----	----	----	----	----
**	74001	4.	----	63.00	----	----	44.20	44.20	286.00	0.	31.80	0.111
**	74002	4.	1861.	----	1661.	1495.	2.77	2.77	----	0.	0.00	----
	74003	19.	----	2.40	142.	128.	2.87	3.77	9.44	0.	0.00	0.000
**	74004	18.	----	22.00	2946.	2148.	4.86	4.86	30.70	0.	0.00	0.000
**	74005	4.	1879.	----	613.	552.	4.90	4.90	----	0.	0.00	----
**	75001	4.	----	27.30	----	----	64.70	64.70	379.00	0.	27.20	0.072
	75002	4.	----	9.00	642.	567.	4.98	5.00	13.51	----	----	----

TABLE A3.4 (continued)

	RESNO	TYPE	DATE	NYIELD	GROSSCAP	NETCAP	NATAREA	TOTAREA	ADFLOW	COMPCODE	COMPFLOW	COMP/ADF
**	75003	4.	1894.	202.00	40714.	38678.	40.90	40.90	245.18	0.	13.64	0.056
**	76001	4.	1941.	299.00	84839.	80597.	32.20	63.46	170.70	0.	21.78	0.128
	76002	4.	1908.	2.90	300.	241.	3.04	3.04	20.90	0.	1.36	0.065
**	76003	4.	1910.	7.80	828.	682.	0.00	28.33	0.00	0.	0.00	----
**	76004	4.	1967.	----	----	2280.	13.10	13.10	----	0.	7.45	----
**	77001	4.	1961.	----	----	----	17.56	----	45.46	0.	4.55	0.100
**	79001	4.	1935.	23.90	2909.	----	7.88	8.50	37.49	----	----	----
**	80002	4.	----	----	----	----	11.72	----	31.15	0.	10.37	0.333
**	80003	1.	----	----	131519.	----	856.00	----	2882.26	2.	----	----
	80004	----	----	----	82980.	----	----	----	----	----	----	----
	80203	----	----	----	9062.	----	----	----	----	----	----	----
	80303	----	----	----	1246.	----	----	----	----	----	----	----
	80403	----	----	----	849.	----	----	----	----	----	----	----
	80503	----	----	----	1133.	----	----	----	----	----	----	----
	80603	----	----	----	35400.	----	----	----	----	----	----	----
**	81002	4.	----	----	----	----	18.20	18.20	51.56	0.	8.64	0.168
**	82001	4.	1973.	20.00	19200.	----	15.20	----	66.26	4.	----	----
**	82002	4.	1892.	----	----	----	10.47	----	29.26	0.	1.70	0.058
**	82003	4.	1927.	22.73	----	----	12.93	----	55.47	0.	2.99	0.054
**	83002	4.	1886.	47.51	----	----	12.10	----	48.40	0.	7.27	0.150
	83003	4.	1845.	2.23	----	----	3.20	----	10.52	0.	0.45	0.043
**	83004	3.	1906.	3.68	----	----	9.87	----	19.61	0.	2.27	0.116
	83005	19.	1877.	6.41	----	----	4.63	----	9.32	0.	1.36	0.146
	83006	4.	1907.	16.59	----	----	2.50	----	7.19	0.	2.73	0.380
	83008	4.	1914.	1.50	----	----	1.10	----	2.94	0.	0.77	0.262
	83009	4.	1932.	2.61	----	----	1.83	----	5.82	0.	1.32	0.227

TABLE A3.4 (continued)

	RESNO	TYPE	DATE	NYIELD	GROSSCAP	NETCAP	NATAREA	TOTAREA	ADFLOW	COMPCODE	COMPFLOW	COMP/ADF
	83010	4.	1940.	6.57	----	----	4.80	----	14.99	0.	2.70	0.180
	83011	4.	1940.	0.49	----	----	1.70	----	4.98	0.	0.73	0.147
	83202	19.	1943.	----	----	----	----	----	----	0.	0.00	----
	83204	19.	1947.	----	----	----	----	6.00	18.10	0.	0.00	0.000
	84001	----	1895.	2.20	94.	----	----	----	----	----	----	----
	84002	----	1874.	1.00	146.	----	----	----	----	----	----	----
	84003	----	1905.	----	150.	----	----	----	----	----	----	----
##	84006	4.	1956.	131.98	25485.	----	46.12	----	211.39	0.	25.14	0.119
##	84007	4.	1930.	33.19	----	----	25.31	----	73.92	0.	13.64	0.185
	84008	4.	1916.	21.22	----	----	5.40	----	14.50	0.	4.42	0.305
	84009	4.	1906.	8.84	----	----	4.26	----	13.30	0.	1.70	0.128
##	84010	4.	1872.	23.26	----	----	9.65	----	34.11	2.	9.60	0.281
	84012	4.	1838.	4.34	----	----	5.35	----	12.22	0.	1.45	0.119
	85002	----	----	----	----	----	----	----	----	3.	91.00	----
##	86001	5.	1950.	----	35679.	----	17.00	80.00	----	0.	0.00	----
##	86002	1.	----	----	----	----	39.43	56.98	268.80	14.	22.73	0.085
##	86003	5.	----	----	----	----	7.87	----	----	0.	0.00	----
	86004	5.	----	----	13000.	----	9.89	----	----	----	----	----
	87001	5.	----	----	----	----	9.99	----	----	----	----	----
##	88001	1.	----	----	----	----	10.75	----	58.90	10.	9.09	0.154
	88002	1.	----	----	----	----	----	----	18.04	12.	----	----
##	89001	1.	----	----	----	----	37.50	46.00	189.30	10.	9.09	0.048
##	89002	1.	----	----	17800.	----	804.00	----	4575.00	13.	455.00	0.099
	89202	16.	----	----	10050.	----	5.44	22.80	42.49	----	----	----
	90001	----	----	----	94578.	----	----	----	----	----	----	----
	91001	1.	----	----	----	----	----	----	----	----	----	----

TABLE A3.4 (continued)

RESNO	TYPE	DATE	NYIELD	GROSSCAP	NETCAP	NATAREA	TOTAREA	ADFLOW	COMPCODE	COMPFLOW	COMP/ADF
** 91002	----	----	----	43495.	----	373.50	578.50	----	----	0.00	----
** 91003	----	----	----	218040.	----	112.80	----	----	----	0.00	----
** 93001	1.	----	----	----	----	170.53	170.53	869.70	4.	90.92	0.105
94001	1.	----	----	----	----	----	----	----	0.	38.64	----
95001	----	----	----	----	----	----	137.50	----	----	----	----
97001	18.	----	----	----	----	----	----	----	----	----	----
** 97002	4.	----	----	----	----	23.87	----	35.97	0.	0.55	0.015
** 102001	4.	1966.	29.52	7870.	----	32.90	32.90	43.20	0.	3.18	0.074
** 102002	4.	1950.	19.60	1796.	----	35.00	35.00	51.80	0.	1.82	0.035
** 104001	1.	----	----	----	----	27.18	----	88.67	10.	22.73	0.256

NOTE Reservoir numbers are prefixed by 'R' in the text to avoid confusion with W.D.U. gauging station numbers.

While every attempt was made to ensure that data contained in this table are as accurate and complete as possible, it should be noted that many reservoirs are operated jointly with other sources and frequently have complex compensation flow policies. Table A3.5 provides additional information on each reservoir and should be referred to.

Some of the releases shown above may have been changed or under review so for current information on any particular reservoir scheme the reader is advised to contact the reservoir operator directly.

TABLE A3.5 COMMENTS ON RESERVOIRS ON IH RESERVOIR ARCHIVE

Reservoir Number	Comments
Scotland	Area 1
2001	Dam used to supplement low flows for fisheries.
2002	Dam used to supplement low flows for fisheries.
3001	Seasonally varied releases of 227.3 Mld 1 March-30 June; 181.84 Mld 1 July-30 Sept; 90.92 Mld 1 Oct-28 Feb plus freshets from 1 March-30 Sept totalling 21821 Ml/yr to allow for natural spates and at dates agreed by Fisheries Board.
4001	Compensation releases from Torr Achilty generating station via fish ladder of 90.92 Mld plus enough water to maintain flow of 545.5 Mld below tailrace(NH446545). Adflow here=2550.0 Mld.
4002	Maintained flow at Black Bridge(NH372709)-releases from either Glascarnoch or Vaich Res. (Adflow at Black Br=778.05 Mld, Natarea=164.4 km^2, SAAR=2037 mm). Plus freshets above L Garve(NH400610) of 545.5 Mld on 6 occasions Aug-Oct, each lasting 48 hrs (Natarea at NH400610=290.75 km^2. Adflow=1149 Mld, Saar=1817 mms). Maintained flow approx 10 miles d/s at Falls of Rogie of 79Mld (Natarea to falls=327.19 km^2, Saar=1778 mm, Adflow=1257.9 Mld).
4005	Seasonal releases via fish Pass: 90.92 Mld March, April, May, July, 54.55 Mld Sept, Oct, Nov, 45.46 Mld Jan, Feb, June, Aug, Dec; plus freshets totalling 2818.52 Ml/yr to allow for natural spates at dates agreed by Fisheries Board.
4006	Water abstracted at Redburn Flume(NH566673). Compensation set at a continuous discharge 27.3 Mld.
4201	Seasonal releases down fish ladder of 90.92 Mld mid March-mid Oct; 22.73 Mld mid Oct-mid March, plus maintained flow of 545.55 Mld on 30 days from mid March-mid Oct (ie freshets).
4401	Seasonal releases of 90.92 Mld mid March-mid Oct, 22.73 Mld mid Oct-mid March, plus maintained flow of 545.55 Mld below fish ladder on 30 days mid March-mid Oct (ie freshets).
5001	Maintained minimum flow in R Farrar at dam(NH325397) of 204.57 Mld. Block grant totalling 13638 Ml/yr for freshets. Dates agreed by Fisheries Board & can be varied. (Natarea to dam=233.5 km^2, Saar=2244 mm); also maintained flow below Culligran G S of 545.5 Mld(at NH380406).
5003	Maintained flow of 68.19 Mld near Fasnakyle(just d/s junction of R Affric & Amhuinn Deabhag, NH310288) with releases at dam of 13.638 Mld 1 Nov-31 May, 40.914 Mld 1 June-31 Oct. Also releases of 190.932 Mld into R Glass d/s of generating statn(NH319296) from Oct-April & 472.784 Mld May-Sept. This will affect the river most. Area taken to be same at both sites ie 275.0 km^2, Saar=2455 mm, Adflow=1618.3 Mld.
5004	See 5204.
5201	Maintained minimum flow of 136.38 Mld below junction of R. Farrar and a tributary Uisge Misgeach(NH221389) & 90.92 Mld in Uisge Misgeach, at its junction with Allt Garbh-Choire(on tributary adjacent to dam) Up to 9092 Ml/year can be released as measured at a point below junction of Uisge Misgeach and R Farrar at dates agreed by Fisheries Board. (Natarea to NH221389=170.5 km^2, Saar=2448 mm, Adflow=998.6 Mld).

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TABLE A3.5 (CONTINUED)

Reservoir Number	Comments
5204	Releases from 5204 & 5004 together must be sufficient to maintain flow in R Beauly below Aigas & Kilmorack Generating Statn of not less than 1136.5 Mld.
6001	Seasonal releases of 159.11 Mld May-Oct; 45.46 Mld Nov-April plus freshets totalling 43778 Ml/yr including natural spates and counting 1 natural spate as a freshet.
6002	Seasonally variable discharge via fish ladder of 68.2 Mld Sept-March (minm release); 295.5 Mld April-Aug at fish ladder (maintained flow) plus freshets on not less than 30 days/yr during which total flow in R Garry is not less than 1659 Mld. (Adflow at dam (NH275020)=20 Mld). Also flow in R Garry below Invergarry G S, when added to that in R Moriston below Glenmoriston must not fall below 772.8 Mld.
6003	Part of Foyers scheme. No compensation requirement for L Mhor.
6201	Constant discharge in R Moriston of 90.92 Mld at Dam (NH184100) and freshets on 22 days during which flow >454.6 Mld.(Natarea=85.75 km^2, Saar=3034 mm, Adflow=639.9 Mld). Below Ceannacroc generating statn (NH228108) flows of not less than 454.6 Mld are maintained (Natarea=175.5 km^2, Saar=2830 mm, Adflow=1206.8 Mld).
6202	Constant compensation discharge of 90.92 Mld at dam (NH070020) plus freshets on 10 days in Oct of 682 Mld.
13001	Loch Lee- compensation=29.549 Mld but can be varied depending on natural flow inferred from neighbouring Mark tributary. If flow in Lee (naturally) 29.549 Mld can reduce compensation provided it is always 6.82 Mld. Freshets once a month up to 120.92 Mld for 48 hrs, as long as natural flow 136.4 Mld totalling 181.84 Ml/yr available as block grant. Flow of 13.638 Mld must be maintained at fish pass.
14003	Joint yield with 14004 quoted.
14004	Joint yield with 14003 quoted.
15002	Seasonally variable releases 3.41 Mld Oct-April; 6.82 Mld May-Sept.
15003	Seasonal releases & freshets at Dam (NN501420). (Adflow=628.4 Mld). Maintained Flow of 190.93 Mld for 4 months, 136.38 Mld for 8 months, plus freshets totalling 9683 Ml/yr, including natural spates.
15005	Seasonal releases to maintain minimum flow in R Lednock above Deils Cauldron, a long distance downstream (NN768236), of 54.552 Mld Oct-Dec, 40.914 Mld Jan-March, 27.276 Mld April-Sept (Adflow=207.25 Mld).
15008	Minimum flow below dam (NN943578) of 181.84 Mld plus enough water to ensure flow in R Tummel below Faskally Res of 1136.5 Mld. (Same area to generating statn) Adflow=6141.4 Mld.
15012	Seasonal releases below generating statn (NN440570) of 68.19 Mld mid May-mid Nov, 45.46 Mld mid Nov-mid May, plus maintained flow in Gaur of not less than 1818.4 Mld (at dam;-Adflow=814.6 Mld; Natarea=169.63 km^2, Saar=2078 mm; at generating statn;-natarea=236.82 km^2, Saar=1986 mm).

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TABLE A3.5 (CONTINUED)

Reservoir Number	Comments
15203	Arrange releases to maintain compensation between L Lyon & Stronuich Res, the same as that below Stronuich.
15208	Releases made below Tummel to ensure flows of 204.57Mld (Average), 181.84 Mld(Minimum) from May -Nov, 90.92 Mld(Minimum) from Dec-April, plus up to 89602 Ml/yr (including other compensation water) as a block grant.
15508	Minimum flow of 31.82 Mld at Trinafour Bridge(Natarea=56.56 km^2, Saar=1382 mm, Adflow=165.3 Mld). Maintained flow at junction of Errochty Water & R Garry (excluding Garry catchment) of not less than 68.19 Mld May-Nov, 45.46 Mld Dec-April, plus block grant as required,but not exceeding 2273 Mld (Natarea to confluence=91.75 km^2, Saar=1293 mm, Adflow=245 Mld). Minimum flow of 31.82 Mld at Trinafour Bridge(Natarea=56.56 km^2, Saar=1382 mm, Adflow=165.3 Mld). Revised gross yield of 46.824 Mld.
17003	Compensation in 2 directions to R Endrick & R Carron. (A) To R Endrick - minimum compensation flows of 2.864 Mld 1 May to 30 Nov, and 4.091 Mld 1 Dec to 30 April. Freshets from stored summer water are at discretion of board at rate not more than 45 Mld and volume not more than 181.84 Ml/yr. No abstractions from R Endrick if flow is less than 1.23 Mld or if Carron Res level is less than 737.92 ft OD. (B) To R Carron - flow at Longhill Weir (NS772846) not less than 41.82 Ml (Adflow=282.5 Mld, Natarea=77.7 km^2) L Coulter, Buckieburn, Faughlin, Earlsburn 1 & 2, and Carron form the Carron scheme.
17011	Dam raised 1933. Compensation originally set for mills at 3.41 Mld over 12 hrs.
17015	Operated with Drumbowie, Little Denny Res; values are combined.
18001	Block grant at request of distillers & TRPB of 90.92 Ml/yr at rate not exceeding 22.73 Mld, otherwise constant discharge. Compensation taken from Glendevon but entering R Devon downstream of Castlehill Res. Also 1136.5 Ml available in last 3 months of each year for fishing at maximum rate of 227.3 Mld.
18002	Pre 1946 Compensation=10.3 Mld.
18004	Compensation from Venachar from whole Katrine system, pre 1965 146.493 Mld 11 am-11 pm; 34.84 Mld 11 pm-11 am. Since Finglas total compensation from Venachar=120.63 Mld; yield of Venachar=136.4 Mld; yield of Katrine, Finglas, Venacher together is 629.6 Mld (gross).
18005	Original compensation=10.456 Mld reduced to 1.364 Mld in 1968 by water order. Gross yield 70.463 Mld.
18015	Zero compensation to stream; pipeline supplies mill directly 1.34 Mld.
18204	Operated conjunctively with Venachar and used to top it up.
18304	Gross yield 127.3 Mld; compensation and overflow go to Venachar; since Finglas an additional 22.7 Mld compensation is required from Venachar. Supply to Katrine via a tunnel.
18401	Constant compensation=29.2 Mld, but released below 18001?
18404	Storage reservoir between Katrine & Venachar.

TABLE A3.5 (CONTINUED)

Reservoir Number	Comments
18504	Dam raised 1919, compensation to Venachar, gross yield = 365.95 Mld. No compensation agreement required.
19003	Operated with Loganlea; joint yield & compensation given.
19009	Operated with 19209; joint compensation given.
19011	Torduff, N Pentland springs joint compensation & yield.
19013	Morton 1 & 2 operated together; joint yield given.
19203	Operated with Glencorse (19003); joint yield & compensation given.
19209	Enlarged 1890 to present volume; joint compensation with 19009.
21001	Yield of Fruid & Talla combined=135 Mld. Original yield of Talla + aquaduct=68 Mld, in 1936 yield increased by reducing compensation flows. 1950 intake constructed to Talla from Menzion Burn. Seasonally varying releases of 16.593 May to Sept and zero from Oct to April. No freshets. Releases from Fruid, released to river downstream of Talla.
21002	21002 & 21003 operated together. Combined yield less than 22.73 Mld. Seasonally varying releases of 4.019 Mld May to Sept, 2.273 Mld for rest of year. Freshets released April to October.
21003	21002 & 21003 operated together. Seasonally varying releases of 2.864 Mld May to Sept and 1.59 Mld for rest of year. Combined block grant of 136.4 Ml, with maximum freshet release of 13.64 Mld.
21006	Seasonally varying flows. Summer 11.365 Mld, winter 2.213 Mld with block grant allowance of 1660.0 Ml with maximum rate of release 90.9 Mld. Used for freshets.
21007	Seasonally varying flows. 14.365 Mld March-May, Sept to Dec; 8.975 Mld from Dec-March; 17.957 Mld from May to Sept. Complex freshet releases on specified dates averaging 4 per month in summer and autumn.
21010	Seasonally varying releases. Summer flow of 40.914 Mld, winter flow of 13.638 Mld and block grant of 909.2 Ml. Large flexible block grant for freshets when required. On completion of works on St Mary's loch proposed compensation to Yarrow Water is 100 Mld in summer, 54.55 Mld in winter, block grant of 7364.4 Ml/yr.
77001	Built in 1960s.
80002	Compensation figure approx.
80003	Compensation varies between 22.73 Mld to 54.22 Mld. Used to keep Tongland Res topped up for hydroelectric generation.
81002	Compensation figure approx.
82001	Constant discharge of 0.455 Mld to filter works; 9.09 Mld released to river below filter works. Total 9.55 Mld. Block grant of 682 Ml for freshets at rate 1.50 Ml/hr for 18 hrs. Gives average compensation of 11.41 Mld. Net yield 90.92 Mld (compensation 11.1% of gross yield of 102.34 Mld).

TABLE A3.5 (CONTINUED)

Reservoir Number	Comments
82003	Compensation 11.5% of gross yield of 25.717 Mld.
83002	Original compensation (Camphill only) =6.819 Mld. Increased after construction of Muirhead to 7.274 Mld (13% joint gross yield of 54.779 Mld).
83003	Original compensation=2.046 Mld reduced to 0.455 Mld in 1969.
83004	Knockendon discharges into Caaf and compensation from Caaf is from both reservoirs.
83204	Discharges into 83004.
84006	Water order 1948. Incorporates formula for increase of compensation if average rainfall is higher than originally estimated. Originally set at 20.457 Mld increased to 25.139 Mld corresponding to final assessment of rainfall.
84007	Original compensation(1913 Act)=17.73 Mld, reduced to 13.64 Mld in 1947.
84008	Operated with 84009. Joint compensation 25.639 Mld.
84009	Gross yield 10.547 Mld.
84010	Seasonally variable flow. Nov-April 6.546 Mld, (also Sat & Sun all year), May-Oct 6.108 Mld in addition to 6.546 Mld=12.654 Mld(Mon-Fri only).
84012	Compensation is 25% gross yield. Some of compensation discharged into stream below reservoir, rest from aqueduct.
86002	Constant discharge as measured at Falls of Drimlee. (Falls(NN160190):-Natarea [illegible]9.43 km^2, Saar=2884 mm, Adflow=268.8 Mld), also 8 freshets (2/month June-Sept). Each freshet lasts 48 hrs during which total flow is not less than 204.57 Mld as measured at confluence of Kilbl[illegible] Burn & R Shira, 4 miles downstream.
88001	Maintained flow at Oude Power Statn(NM870150)-minimum flow of 9.092 Mld. Adflow=58.9 Mld.
88002	Must release enough water to maintain minimum flow of 2.273 Mld from 1June-15 Oct plus any other quantities as agreed by the Fisheries Board so total/yr is not more than 309.13 Ml (at dam(NM865145), Natarea=3.25 km^2, Saar=2400 mm, Adflow=18.0 Mld).
89001	Constant maintained flow below junction of R Nant with Allt Poll An Dubhaich. Adflow=189.3 Mld.
89002	Seasonally variable compensation flow at Dam (NM879045). Adflow=4575 Mld. (a) 1 April-30 Sept on 120 days, flow varies night & day (1364 Ml day, 909 Ml night) & freshets on 26 of these days of more than 2727 Mld. On remaining 63 days flow is 636 Mld. Therefore average flow is 756 Mld. (b) 1 Oct-30 Nov, flow not less than 682 Mld. (c) 1 Dec-31 March, 455 Mld plus freshets on 3 days from 15-31 March of up to 2727 Mld. In summer if inflow to reservoir is less than 1364 Mld compensation flow will be limited to the same as the inflow.
91001	Maintained flow of 340.95 Mld downstream of Mucomir generating station (NS179843).

TABLE A3.5 (CONTINUED)

Reservoir Number	Comments
93001	Compensation is constant discharge of 45.46 Mld at fish ladder. Through tailrace of Morar Generating Station flow of not less than 90.92 Mld plus block grant of up to 7501 Ml/yr. Adflow at both=869.7 Mld.
94001	Compensation released through tailrace of Kerry Falls Generating Station sufficient to maintain continuous flow of more than 38 Mld provided that level of L Bad An Sgalaig is in excess of 357.5 ft OD. If below this, amount released=15.911 Mld.
97002	Minimum release at dam(ND085596) of 0.546 Mld. (Adflow at dam=35.97 Mld; Saar=943 mm). Also minimum maintained flow of 2.455 Mld at ND140608 (Natarea=436.92 km^2, Saar=1019 mm, Adflow=766.11 Mld)
104001	Compensation=maintained flow below generating station-assume at dam(NR707287).
Northumbrian WA Area 2	
23006	Group of 8 reservoirs receive water pumped from R Tyne at Wylam.
23007	Seasonally varying flows. April to Sept 25.0 Mld, Oct to March 22.73 Mld, block grant allowance of 827 Ml for freshets.
23010	Compensation releases seasonal: April-Nov 114 Mld, Dec-March 57 Mld.
23203	Colt Crag Res feeds into Little Swinburn.
23204	West Hallington receives water pumped from R North Tyne at Barrasford.
23206	Varying compensation in two halves of water year.
24203	Waskerley within catchment of Tunstall.
25001	Water used for raw industrial supplies only.
25002	Water used for raw industrial supplies only.
25003	Water used for raw industrial supplies only.
25009	Regulating reservoir for Tees in summer, otherwise constant prescribed flow at Broken Scar of 127.3 Mld, so releases must be 127.3 Mld plus abstractions.
25204	Selset within Grassholme catchment.
Yorkshire WA Area 3	
27005	Compensation based on control rules and depends on reservoir level and time of year.
27009	2-3 freshet releases a year.
27013	Compensation revised in 1969 to give lower summer (0.382 Mld) than winter flows (0.782 Mld).

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TABLE A3.5 (CONTINUED)

Reservoir Number	Comments
27016	Prescribed flow at Springhead Weir (SK026378) maintained by 27017, 27216, 27316. Flow at Springhead Weir must be 11.14 Ml (over 12 hrs) Mon-Friday, 5.55 Ml (over 6 hrs) Saturday. Equivalent weekly flow quoted of 8.7 Mld. Millowners Committee control top 3 ft 5 ins of TWL of reservoir.
27024	Hard to accurately establish natural catchment.
27027	Maintained flow at High Greenwood (SD 973309) from releases from either Widdop or Walshaw Dean.
27030	Releases vary with time of day. 0600-1800 hours Mon-Sat 18.01 Mld, 1800-0600 hours Mon-Sat 3.4 Mld, Sundays 3.4 Mld.
27032	Compensation from either Ogden or Mixenden. Same compensation figure quoted for both reservoirs.
27033	Compensation from either 27032 or 27033. See 27032.
27034	Large indirect catchment.
27036	Catchment area poorly defined.
27037	Catchment area poorly defined.
27038	Compensation at Millowners discretion.
27039	Millowners Committee. Weekly compensation fixed but hourly and daily amounts can vary.
27041	Millowners Committee. Weekly compensation fixed, but hourly and daily amounts can vary.
27043	Maintained flow at SE 61024 which must be maintained by releases from either Winscar or Windleden Res, such that it is not less than 9.09 Mld Nov-Apr, 11.28 Mld May-Oct.
27044	Compensation based on control rules since June 1979, 3.87 Mld when above prescribed reservoir level for time of year and 2.74 Mld when below prescribed level.
27045	Releases based on control rules (dependent on time of year and reservoir level). 36.4 Mld released when above prescribed level, 26.1 Mld when below prescribed level. Compensation linked to Rivelin system.
27049	Compensation based on control rules (dependent on time of year and reservoir level). 12.02 Mld when above prescribed level, 9.092 Mld when below prescribed level. Flow changes weekly.
27050	Millowners interest. Now operated using control rules based on reservoir level and time of year Compensation=21.0 Mld when reservoir is above prescribed level, 16.0 Mld when below prescribed level.
27051	Compensation can be reduced provided corresponding increase from Damflask with agreement of associated millowners.

TABLE A3.5 (CONTINUED)

Reservoir Number	Comments
27202	Compensation for Roundhill discharged at Leighton. Assume 9.11 Mld at Leighton includes this discharge.
27243	Compensation in conjunction with 27943, Winscar.
Anglian WA	Area 4
29001	Pumped storage Reservoir.
29002	Part of Trent-Witham-Ancholme scheme, regulates R Ancholme. Pumped storage reservoir taking water from R Witham.
29003	Part of Trent-Witham-Ancholme scheme-storage reservoir to supply Grimsby, supply only.
31002	After 1976 drought, safe yield reduced to 13.64 Mld.
31003	Empingham/Rutland water filling started Feb 1975. Small natural catchment-inlet aqueducts from Wansford on Nene and from Tinwell on R Welland.
32002	1913 Act-continuous compensation flow 2.05 Mld.
32004	1943 Act-set compensation flows. Seasonally varying flows May-Nov 2.73 Mld, Dec-April 0.91 Mld, plus block grant of 454.6 Ml at a maximum rate of discharge of 32.73 Mld. Water bank has been used only once in summer 1959. Formed precedent for Stocks Reservoir.
32005	Reservoir now abandoned by AWA.
33002	Compensation varies May-Oct 113.8 Mld, Nov-Mar 31.82 Mld.
37002	Pumped storage reservoir with pumped abstraction from Stour above 13.64 Mld in winter, 18.18 Mld in summer (thresholds).
Southern WA	Area 6
40001	Seasonally varying flows. May-Oct 5.5 Mld, Nov-April 3.6 Mld.
40002	Compensation reduced to 1.63 Mld in 1976 drought. Impounding and pumped storage from Teise at Smallbridge; (TQ712385). River regulation to abstraction at Maidstone. Design yield is at Springfield with Teston prescribed flow=352 Mld.
40003	Proposed new reservoir. Compensation to protect downstream abstractors set at 20% annual average flow; some impounding, mainly pumped storage from Stour for direct supply.
40004	Pumped storage reservoir, abstraction from Eden for direct supply, seasonally varying releases May-Oct 0.3 Mld, Nov-April 0.1 Mld.
40005	Net reservoir volume given. Direct supply/impounding reservoir incorporated in Darwell. Licence is prescribed flow of 26.0 Mld for Rother at Udiam. Seasonally varying reservoir releases. April-Sept 0.8 Mld, Oct-March 0.3 Mld.
40006	Small impounding reservoir for direct supply.

TABLE A3.5 (CONTINUED)

Reservoir Number	Comments
41001	Pumped storage for direct supply (from Ouckmere).
41002	Impounding with some pumped storage from Ouse for river regulation and abstraction at Barcombe. Yield given is at Barcombe over & above previous abstraction of 19.3 Mld, compensation given as 0.9 Mld plus regulating releases to maintain flow of 13.6 Mld below R Ouse confluence. Refill pump site at TQ332283.
Wessex WA	Area 7
43001	Inflow to reservoir is divided-first 1.4 Mld is piped round reservoir for compensation water; second 1.4 Mld goes into reservoir; any inflow above 2.8 Mld is split 50:50.
52005	Compensation is split: 0.46 Mld to Ourxy Pool stream, 0.68 below Ashford (0.68 Mld flows from Hawkridge to Ashford).
52007	8.64 Mld 15 May to 30 Nov, rest of year 2.27 Mld.
52008	Seasonally varying releases; winter 0.0546 Mld, summer 0.0363 Mld (Exact period not known).
52009	Filled by springs-purely a storage reservoir.
52020	Compensation split into 0.06 Mld below Luxhay Reservoir (ST203178); 0.39 Mld to Sherford Stream(ST223171). Leigh Reservoir(ST197198) also in group.
53002	Compensation releases to River Chew are 14.32 Mld May-Nov, 6.819 Mld Dec-April. Compensation releases to Winford Brock are 3.41 Mld May-Sept, 2.273 Mld Oct-April. However not clear if these are maintained flows after abstraction or releases from 53002.
South West WA	Area 8
45001	Also augments flows on R Exe. Releases are based on abstractions at Pynes (SX921970) and Bolnam Weir (SX949152) and a prescribed flow at Thorverton on R Exe of 273 Mld. Above this, 100% abstraction is allowed. Freshets 455 Ml/yr allowed in addition to constant compensation discharge of 9.1 Mld, but it is never requested. It only provides for approx 2 freshets a year.
46001	Compensation, pre 1976, is constant discharge of 8.183 Mld with no freshets. Since then block grant of 829.6 Mld has been introduced for freshets.
46002	Water also pumped to Tottiford Reservoir, see 46003. Yield given (23.87 Mld) is total yield of Fernworthy, Kennick, Trenchford and Tottiford. Fernworthy used to augment Kennick, Trenchford & Tottiford.
46003	See 46203.
47001	Reservoir augmented by flow along Devonport Leat from R Dart. Water pumped from Lockwell on R Tavy up to Burrator. Therefore pumped storage type reservoir. Constant compensation releases all year. Compensation is only 3% Adf, confirmed by SWWA.
48001	Start impounding autumn 1983. Compensation used with Siblyback to augment flows in R Fowey. Block grant allowance of 454.6 Mld for freshets.

TABLE A3.5 (CONTINUED)

Reservoir Number	Comments
48203	Regulates 2 rivers-Fowey and Withy Brock. Prescribed flows at abstraction points of 13.6 Mld (Fowey at Trekeivesteps(SX 227698)) and 95.4 Mld at Restormel (SX097625). Releases changed automatically.
50001	Normally just constant compensation flow is released. Under abnormal circumstances may also make regulation releases to support abstractions downstream at Torrington. First release known to SWWA was July 1983 - applied for drought order to make regulation releases. Maximum allowable release=10.23 Mld - release only required when river at Torrington is less than 78.42 Mld. SWWA wants to reduce compensation by 3.86 Mld and use water saved for regulation/freshet releases.
Welsh NWDA - Area 9	
55001	55001, 55201, 55301, 55401, 55501, 55601 - are all Elan Valley reservoirs and are operated together. Regulating reservoirs for Wye - control point at Redbrock. Pre Claerwen (ie pre 1952), compensation flow released for all Elan Res at 55001=123 Mld. Compensation then increased to 132 Mld (variable); reduced on 24/9/75 to 118 Mld, with water saved used to support regulated yield of 30 Mld. Enquiry proposed to reduce compensation further to 68.2 Mld + freshets of 68.2 Mld, and regulating release of 164 Mld. When reservoir levels drop below a specific level, maximum compensation is reduced. Complex arrangement - 1973 feasibility study to raise dam will increase net yield to 2500 Mld and storage to 600,000 Ml. Redbrook control pt - catchment area =4010 km^2, Adflow here =6360 Mld, prescribed flow here =605 Mld, Adflow at Caban Coch=657.5 Mld, total impounded area=182.1 km^2. WNWDA think compensation flows are accurate to + or - 2.3 Mld.
56002	Regulating reservoir for River Usk, control point Trostrey(area to Trostrey = 927 km^2, Adflow=2450 Mld). Adflow quoted is at Usk res. Compensation flow at dam quoted (constant discharge), but also have regulation releases.
56003	Supply and regulating reservoir.
56004	Seasonally varying compensation - for salmon spawning (tributary of Usk). Nov-April 25 Mld, May-July 18.2 Mld, Aug-Oct 13.6 Mld. No freshets. Adflow figure from Welsh probably includes Clydach catchwater. -Reduced by ratio of natural/total area to give natural Adflow of 98.76 Mld.
56005	Regulating reservoir for Usk; control point at Trostrey. Net yield includes pumped inflows from Usk. Natural Adflow quoted.
56009	Seasonally varying flows. Nov-Aug 2.068 Mld, Sept-Oct 3.274 Mld.
56010	Catchwaters. Adflow includes catchwaters.
56011	Catchwaters. Adflow includes catchwaters.
57001	57001, 57201, 57301, form the Taf Fawr Group of reservoirs. Compensation quoted for 57001 is a normal release but reservoir can be operated with 57002 (Taff Fechan), such that a reduction in compensation at Llwynon (from 18.2 to a maximum of 9.1 Mld) can be made up by an increase at Pontsticill of same amount. Reverse situation not covered by licence yet - reservoirs are operated like this to increase the net yield. Compensation can be increased by up to 6.82 Mld.

TABLE A3.5 (CONTINUED)

Reservoir Number	Comments
57002	See comments for 57001 - can be operated together. 'Normal' compensation release is quoted. Otherwise known as Pontsticill Res.
57003	Adflow quoted includes catchwater.
57004	No natural catchment. Raw water storage only.
57007	Adflow includes catchwaters.
57302	Joint yield of Neuadd Res alone =18.2 Mld.
58002	No longer used for supply. Catchwaters included in Adflow calculation.
58004	Compensation piped direct to NCB. Adflow includes catchwaters.
59001	Natural combined yield with U Lliw=8.41 Mld, but also used as pumped storage reservoir from Towy system.
59201	Reservoir rebuilt in 1976, original in 1870, but due to fault always operated at reduced yield.
60001	Regulating reservoir for Towy-control point at Nantgaredig; under construction 1968-72. 20% hands off flow, freshets, catchment area to regulation Pt=1090 km^2, Adflow=3360 Mld.
61001	Regulating reservoir for E Cleddau-control Pt at Canaston Bridge. Catchment area to regulating point = 183 km^2, Adflow = 513 Mld. Compensation quoted is at dam.
61201	Yield quoted includes pumped inflows from an adjacent catchment.
62001	62001, 62002 operated together - connected by pipe. Compensation is a constant discharge plus block grant allocation of 0.98 Ml in each of June, July, Aug, Sept for freshets requested by fisheries (total = 3.92 Ml).
62002	Area, Adflow and net yield figures quoted do not include 62001. Compensation is a constant discharge plus block grant allocation of 2.18 Ml in each of June, July, Aug, Sept for freshets. (Total 8.72 Ml).
63001	Compensation flow determined by fisheries interests.
64002	Compensation restricted by lake level.
64003	High compensation award secured by millowners.
65002	Augments low flows in Afon Gwyrfai and supports downstream abstraction subject to a maintained flow at Nant Mill of 18.18 Mld if lake drawdown less than 1m or 13.64 Mld if drawdown is excess of 1m. Also freshets - allow flows to fall to 11.36 Mld on up to 30 days in any 40 days so water is available for freshets of up to 204.6 Mld.
65003	Spillway raised in 1976 which increased yield to 9.55 Mld from 8.6 Mld. High compensation award secured by millowners (Brynkir Woollen Mill) in addition to compensation, 11.4 Mld released for abstraction at Dolbenmaen plus freshets of 45.56 Mld.

TABLE A3.5 (CONTINUED)

Reservoir Number	Comments
65006	Adflow (with catchwaters) = 3.2 Mld. Natural Adflow obtained by proportioning areas.
66001	Llyn Cowlyd fed by complex series of catchwaters including spill from Llyn Dulyn. Adflow of 177 Mld (probably includes catchwaters) split as follows - WWA to supply 23 Mld, CEGB hydro-generation 154 Mld.
66002	Abandoned as a supply res.
66003	Regulating reservoir for Aled-control point at Bryn Aled; under construction 1974-76.
66005	Area figure is an estimate.
66007	Area and yield figures include Melyn Llyn.
66008	Area and yield figures include Dolwen Res.
66203	Regulating reservoir for Aled-control Pt at Bryn Aled. Catchment to regulation point=70 km^2, (Adflow = 138 Mld).
67001	Original compensation set by 1907 Act at 16.366 Mld (33% yield). Amended in 1929 to seasonal flows, April-Sept 13.64 Mld, Oct-March 6.819 Mld. NWWA estimate Adflow as 60.9 Mld.
67002	Regulating reservoir for Dee-control point at Chester Weir (364 Mld); area of catchment to regulating point=1820 km^2, Adflow=3180 Mld. Under construction 1957-65. Area includes catchwaters. Brenig, Tegid, Celyn operated together.
67003	Under construction 1974-76 Brenig. Tegid, Celyn operated together; used for regulation in droughts only. Summer flows 11.4 Mld, winter flows 6.8 Mld.
67004	Nyield in excess of 9.1 Mld.
67008	Area includes catchwaters. Operated in conjunction with 2 other reservoirs. Joint yield and compensation quoted. Accuracy of data before 1969 moderate - poor rating and quality control. Ponding of water in catchment during dam construction. Some overflow into catchment from Llynbran and diversions out of catchment (Pantymaen).
Severn Trent WA - Area 10	
28002	Canal feeder.
28003	Used conjunctively with Leek Aquifer in Potteries area, compensation figure is approx.
28004	Direct supply and pumped storage.
28005	Direct supply, small compensation.
28007	Formerly direct supply, now to regulate Derwent. Compensation quoted is since 1973. Compensation pre 1973=75.77 Mld. Since 1973 flow can be varied though not done until 1980 when reduced to 57.6 Mld. Also prescribed flow on Derwent at Derby of 227.3 Mld after which abstractions cease.
28012	Pumped storage. Insignificant compensation. Small catchment.

TABLE A3.5 (CONTINUED)

Reservoir Number	Comments
28014	Severn, Blithfield & Triassic sandstones used conjunctively by S Staffs Water Company.
28016	Mix of direct supply and pumped storage. Minimum flow of 1068 Mld. at Tony Bridge Nr Derby, now reduced to 682 Mld.
28207	Formerly direct supply, now to regulate the Derwent.
28307	Formerly direct supply, now to regulate the Derwent.
54002	First filled Jan 68. First regulating reservoir for Severn with releases made to maintain residual flow at Bewdley to support downstream abstractions, provide flood storage drawdown and and generate HE. (a) 1963 Clywedog Res Joint Authority Act - uniform continuous compensation flow of 18 Mld plus any additional water to maintain prescribed flow to 727 Mld at Bewdley (1:50 yr return period). Extra releases to give flood storage in reservoir and provide for extra abstractors. 18 Mld used for HE generation. These rules were unsatisfactory in 1976 drought and over releases made as 4 day travel time to Bewdley. Few regulating releases needed up until 1975. Compensation was measured at Cribynau GS (WDU 54913) at SN944855 until 1979. (B) In 1980 Act amended. Conditional prescribed flow is now 850 Mld at Bewdley(SO782762) (WDU GS 54001) averaged over 5 days, subject to a max release - measured at Clywedog at Bryntail at dam (WDU GS 54081; NGR SN913868). Area to dam=49.0 km^2, Saar(41-70) to dam=1786 mm, Adflow to dam=165.929 Mld; area to Bewdley=4325 km^2, Saar=952 mm, Adflow=6114.25 Mld. (C) 1984-proposed to operate Shropshire GW scheme, Clywedog and combined system; prescribed flow at Bewdley will be maintained. Maximum release will be 500 Mld from Clywedog, 25 Mld from Vyrnwy, 225 Mld Shropshire GW to support increased abstraction.
54003	Formerly Liverpool Corpn direct supply, now river regulation in conjunction with Clywedog compensation. (A) 1880 Act - continuous flow of 45.5 Mld plus freshets of 182.5 Mld on 4 consecutive days in each month from March to October irrespective of state of river. (Avg compensation over year=61.37 Mld). Compensation used to generate hydroelectricity since 1942. (B) Hamlin showed that redeployment of freshets made possible an extra 50 Mld for abstractions and uniform flow a further 14 Mld. Not implemented. (C) Since 1967 additional drawdown releases to (A) of up to 360 Mld have been made for flood mitigation. (D) Since 1979 compensation flow 45.5 Mld when Cownwy flow 5 Mld; 22.7 Mld when Cownwy flow 5 Mld. (WDU GS 54086-SH99179). Catchment average flow is 5 Mld for approx 2/3 of time. Compensation is gauged at Vyrnwy Dam (WDU GS 5003). Total catchment contributing to Vyrnwy=94.25 km^2, made up of 73.90 km^2 direct to dam, 12.95 km^2 from Afon Cownwy diversion, 7.398 km^2 from Marchnant diversion. Water is diverted from the headwaters of these tributaries by tunnel.
54008	Pumped storage reservoir filled from R Leam at Eathorpe.
North West Water Authority - Area 11	
69003	Excludes compensation to Musbury catchment of 1.71 Mld.
69005	Compensation supplemented by Eagley Borehole.

TABLE A3.5 (CONTINUED)

Reservoir Number	Comments
69006	Includes Beson Hill catchwater.
69007	Compensation is 1.145 Mld at Brushes Clough and 0.818 Mld from Beson Hill.
69010	Includes Chew.
69017	Compensation from each of 3 compensation and supply reservoirs. (a) Delph Res to Delph Brook 4.299 Ml in 12 hours of every day from 5 am to 5 pm. (b) Jumbles Res to Bradshaw Brook. 13.8 Mld. (c) Waysh Res to Bradshaw Brook 2.45 Mld.
69021	Compensation reservoir only.
69022	Statutory compensation =3.155 Mld over 6 days-in practice released over 7 days.
69023	Compensation reservoir only.
69027	Bottoms & Teggsnose joint compensation operated together. Both compensation only reservoirs.
69028	Maintained flow at entrance to Clough Pool 3.319 Mld (SJ943769), with minimum release from Lamaload of 0.682 Mld and maximum obligatory release of 1.81 Mld.
69029	Maintain mean daily flow of 68.2 Mld at Melandra, subject to maximum daily release of 45.46 Mld and minimum daily release of 22.73 Mld.
69032	Maintain mean daily flow of 13.64 Mld at Taxal.
69034	Out of service since 1950.
69038	Includes compensation to 3 streams. Measuring device vandalised. Compensations are:- Wardle Brook 0.584 Mld, Knowle Syke Brook 1.136 Mld, Clough House Brook 1.136 Mld.
70002	Bleach Works require 3.63 Mld, water which must be made up from 70002, 70003.
70003	Adlington Reservoir supplies water to bleach works at 1.964 Mld.
70004	Present theoretical capacity 17260 Ml Rivington Compensation divided between 3 streams 1. R Douglas-14.684 Mld continuous discharge 2. R Yarrow-1.041 Mld continuous discharge (originally working days only) 3. Brinscall Hall Print works -3.914 Mld continuous discharge 4. Fill Brook - 1.223 Mld continuous discharge 5. Wraying Mill - 4.892 Mld continuous discharge
71002	1912 Act fixed compensation at 29.8 Mld. Reduced in 1956 Act to 18.18 Mld in May-Sept, 13.64 Mld in Oct-April, plus water bank 909 Ml/yr with a maximum allowable release of 72.74 Mld. Based on precedent of Pitsford Res. As a result of informal agreement between Fylde WB & LRA releases of up to 227 Mld were made on each of 4 days a year to make a total of 909 Ml. This remains the current practice.
71003	1.95 Mld Sun-Fri; 0.975 Mld on Sat.

TABLE A3.5 (CONTINUED)

Reservoir Number	Comments
71006	Additional releases of 0.909 Mld when abstracting from Sheddon catchment.
71007	Compensation includes 0.713 Mld to Churn Clough Brook & 0.903 Mld to Hod House Brook.
71015	Compensation = 1.282 Mld, Mon-Fri 5am-5pm.
71018	Complex compensation requirements at stream intakes. Reservoirs provide offstream storage.
73007	Compensation water discharge due to leakage only.
73011	Originally use of reservoir controlled by Kentmere Commissioners and releases adjusted to meet requirements of industry downstream. Now unused.
73012	Acts as a regulating reservoir, making releases down to Crooklands intake only when inflows from other tributaries are deficient. Releases ensure flows of 32 Mld along canal to Lancaster(BWB).
75001	Yield fixed by licence.
75003	Part of Lake District system (see 76004). Nyield quoted is for Thirlmere system. Regulating releases to support Derwent rarely made, so classed as 'supply & compensation' reservoir. Additional releases at request of millowners. Originally 13.6% of yield as compensation, reduced to 11.5% by Manchester 1924 Act.
76001	Part of Lake District system (see 76004). Combined mean daily release of 6.43 Mld from 76001 & 76004, also flows in Swindale, Heltondale, Cawdale Beck must not fall below prescribed levels. Nyield quoted is for Haweswater sys.
76003	Periods of dirty water in Eden overcome by drawing on Castle Carrock Res and pumped up to maximum level on subsequent days to recover loss.
76004	Part of Lake District system. Combined yield of system=725.0 Mld, combined compensation=43 Mld, combined capacity=1278[illegible]3.0 Ml.

APPENDIX A4. FAUNAL AND ENVIRONMENTAL CHARACTERISTICS OF SITES RECEIVING COMPENSATION FLOWS FROM RESERVOIRS.

4.1 Study area and methods

4.1.1 Site selection

Reservoirs built to generate hydro-electric power and reservoirs with a major regulating function were excluded from the pool of sites available because the Institute of Hydrology's main interest was in reservoirs whose discharge was released as compensation flow. Emphasis was therefore placed on sampling a wide range of compensation flows from reservoirs throughout the country. Using a comprehensive list of reservoirs prepared by the Institute of Hydrology a total of 31 sites below reservoirs in South-West England, South Wales, the Pennines and the catchment area of the Tweed in Scotland were selected for study (Figure A4.1). Ease of access, absence of pollution and well-monitored discharge were factors important for the final selection. Two unregulated streams which were adjacent to regulated sites were sampled as controls. The full site list is presented in Table A4.1, together with discharge data.

4.1.2 Sampling frequency and methods

Samples were taken in spring (April 10-16, 1983), summer (June 28 - July 4, 1983) and autumn (September 19-25, 1983) downstream of the reservoir out-flows. Fauna was sampled by disturbing the substratum upstream of an FBA pond net (mesh size 900µm) for three minutes across all major biotopes.

Environmental data for each site, subdivision of compensation flows into discharge classes and subsequent analysis followed the approach adopted in FBA Project 103 'The analysis of natural river communities in Great Britain' (Wright et al. 1981). Chemical data were obtained from the relevant Water Authority or River Purification Board. The environmental and chemical variables recorded for the survey are listed in Table A4.2 and a summary of the data for each site is given in Table A4.3.

The procedure adopted for sorting each biological sample is given in Furse et al. (1981) together with a demonstration of the field sampling technique. Each sample was sorted for about two hours in order to obtain as wide a range of taxa as possible. In addition a $\log_{10}$ scale was used to categorise the abundance of animals in each family (<10 animals = 1, < 100 = 2, <1000 = 3, <10,000 = 4, >10,000 = 5).

4.1.3 Data analyses

Emphasis was placed on ordination and classification techniques so that the relationship between unregulated sites sampled for FBA 103 and regulated sites sampled for this study could be demonstrated.

Ordination was carried out using detrended correspondence analysis (Hill & Gauch, 1980) an improved version of reciprocal averaging (Hill, 1973). The ordination arranges the sites mathematically along what is termed an axis of variation. The ordering is such that the two most dissimilar sites, with respect to taxa complement, are furthest apart on the axis. The position of all other sites along the axis, indicated by their ordination scores, reflect their relative similarities to the two ends of the axis. The distance apart of any two sites along the axis is a measure of their dissimilarity. This first axis demonstrates differences in respect of the most important source of variation. This means that if the principal source of variation is ignored further axes can be calculated.

Sites were classified using two-way indicator species analysis, TWINSPAN, (Hill, 1979). This is an improved version of indicator species analysis which classifies both samples and species and constructs ordered two-way tables to show the relationship between them as clearly as possible. Since two-way indicator species analysis is a divisive technique the division of samples into progressively smaller groupings may be continued for as long as seems profitable. The program also constructs a key to the sample classification by identifying one or more differential taxa which are particularly diagnostic of each division in the classification. The key can therefore be used to classify new sites without the need to reclassify all sites.

In addition to these methods the BMWP biotic score (Armitage, 1983) was calculated for all regulated sites and compared with values from unregulated sites from FBA 103. This biotic score provides a measure of the pollution status of a site where in general high scores indicate "clean" conditions and low scores indicate possible pollution. The interpretation of score and average score per taxon (ASPT) is discussed in Armitage (1983).

Detailed descriptions and discussion of the application and merits of these methods for the analysis of freshwater benthic survey data are found in Wright et al. (1981).

4.2 Results

4.2.1 The fauna

A total of 70 families were recorded from the 33 sites when the samples taken in the three seasons were combined. The number of families recorded in single seasons were 63, 61, 61 in spring, summer and autumn respectively. Table A4.5 lists the seasonal variations in numbers of families taken at each site. Ten sites had the highest number of families in spring, 10 in summer and 8 in autumn. The remaining sites had high numbers of families in more than one season.

Examination of the environmental characteristics of both family-rich and family-poor sites showed no obvious relationships with the numbers of families recorded. However there did appear to be a relationship between age of reservoir and family richness, though this could not be proved statistically for the whole data set. Five out of the six richest sites are below reservoirs which are more than 70 years old. In contrast three out of the four poorest sites are below reservoirs which are less than 12 years old. At two of these, Meldon and Boothwood, only 16 and 18 families were recorded respectively.

The number of families taken in the unregulated control site, Sett (36), was the same as that taken in the adjacent regulated site Kinder 1. Further downstream, Kinder 2, which receives Sett water in addition to reservoir discharge, supported 40 families. The site Wearhead, on the unregulated R. Wear had 24 families represented, whereas 35 were found in the adjacent regulated site Burnhope.

Thirty-six of the 70 families recorded occurred in more than 50% of the sites. Of these, 12 were abundant and included stoneflies (Nemouridae and Leuctridae), mayflies (Baetidae), crustaceans (Gammaridae), caseless caddis (Polycentropodidae, Hydropsychidae and Rhyacophilidae), oligochaetes (Naididae, Lumbriculidae) and 33 subfamilies/tribes of chironomids (Orthocladiinae, Tanypodinae and Tanytarsini). In contrast 28 families occurred at nine or less sites and were never abundant.

The full family list for all sites based on three combined seasons' data is presented in Table A4.6 together with information on the abundance and number of occurrences.

4.2.2 Temperature effects

Temperature data were collected at the same time as sampling in spring, summer and autumn and the results are presented in Table A4.4. Diel fluctuations in temperature are known to be slight below reservoirs (Ward & Stanford 1979) but the value of spot readings taken at different times of the day is questionable and it should be stressed that the remarks below are based on very inadequate data. Features to emerge were:-

(i) Temperature ranges within seasons were greatest in the summer.

	Range °C
spring	4.8 - 8.0 (limited data set)
summer	7.7 - 21.0
autumn	8.8 - 14.1

(ii) In the data set as a whole there was no statistically significant relationship between summer temperature and the number of families recorded at a site.

(iii) Sites with the coldest summer temperatures, that is Meldon, Boothwood, Winscar and Fernilee, also had the lowest number of families.

(iv) The three sites with the warmest summer temperatures, Belmont, Gouthwaite and Widdop also had the largest ranges between summer and autumn. All three sites were amongst sites situated 0.5 km below the dam. Gouthwaite supported the highest number of families (49) in the whole data set, but at Belmont and Widdop only 33 and 29 families were recorded respectively.

(v) At the unregulated control sites Sett and Wearhead, summer temperatures were higher and the observed temperature range between spring and summer greater than at the adjacent regulated sites, Kinder 1 and Burnhope.

	Summer °C	Spring °C	Difference °C
Sett	12.2	6.3	5.9
Kinder 1	10.9	6.0	4.9
Wearhead	13.6	6.6	7.0
Burnhope	12.0	5.2	6.8

Seasonal ranges at Wearhead and Burnhope were very similar and the range between all three seasons was slightly greater at Burnhope (7.3) than at Wearhead (7.0).

It is not possible to draw any firm conclusions from these observations. However there are indications at some sites that regulation of the flow is depressing summer temperature values. The degree to which this takes place will depend on several factors including distance from the dam, the level at which water is released from the reservoir and the amount of the discharge (high discharges will be affected less by ambient air temperatures than will low discharges).

More data are required on temperatures, release point and pattern before their relationship to the benthic macroinvertebrate communities found below dams can be assessed.

4.2.3 Ordination

Figure A4.2 presents an axis 1 by axis 2 ordination plot of the 33 residual flow sites. Correlation coefficients between the ordination scores for axes 1-4 and the environmental variables are presented in Table A4.7. Additional variables included in this correlation analysis were date of impoundment, compensation flow (Ml/day) and compensation flow expressed as a percentage of the natural daily flow (see Table A4.3).

Eigenvalues are calculated for each axis in the computer program. These eigenvalues may be regarded as a measure of the relative importance of individual axes and can be used to derive the amount of variance explained by each axis. Most variation (75.6%) is accounted for by the first two axes of the ordination and by using the data in Table A4.7 with Fig. A4.2 it is possible to examine the distribution of sites in relation to environmental variables. Along axis 1 there is a gradation of sites from those situated at high altitudes, with high water velocities and coarse substrata on the right to low altitude, low velocity, fine substrata sites on the left. Along axis 2 there is a gradation from small streams with low pH at the bottom of the figure to larger streams with higher pH at the top. There is also a tendency for sites with low axis 2 scores to have low numbers of families ($r = 0.756$, $n = 33$, $P = 0.001$).

4.2.4 Classification

The relationship between the 268 mainly unregulated sites sampled during the FBA 103 project (Wright et al. 1981) and the 33 sites sampled during this study was investigated by amalgamating the two data sets and classifying the 301 sites at family level using TWINSPAN. Fig. A4.3 presents a dendrogram showing how TWINSPAN groups are developed through successive divisions 1-5. It is provided so that when various groups are referred to in the report their nomenclature and relationship one to another can be readily comprehended.

A dendrogram based on the combined data set showing group membership of sites is presented in Fig. A4.4. Residual flow sites are indicated in parentheses for the 4th level of division when 16 groups of sites have been generated.

The faunal similarity of most of the residual flow sites which was indicated by the initial ordination (Fig. A4.2) is emphasised here where 24 of the 33 sites occupy two adjacent groups (M & N). Table A4.8 lists all sites present in division 5 TWINSPAN groups which contain residual flow sites and provides data on the number of families recorded at each site. Table A4.9 gives data on the mean and variance of nine environmental variables for unregulated and regulated sites within these TWINSPAN groups.

Of the 33 sites, two, Scout Dike and Bottoms/Teggsnose were separated from the remainder at the first division. Scout Dike in group D differed from the unregulated sites in its group in having a steeper slope, being nearer to the true source of the river and having a lower channel depth and discharge. The two sites with which Scout Dike is grouped are both in pool areas of otherwise ripply streams and these would dampen the effect of spates. The second outlying site, Bottoms/Teggsnose in group G was again nearer to the source and had a steeper slope than the other sites in its group. Alkalinity was lower at Bottoms/Teggsnose, but discharge was similar in all sites in the group. Bottoms/Teggsnose is grouped with sites having a fairly stable flow regime as indicated by their Base Flow Indices ranging from 0.63 to 0.86. Values of the Base Flow Index (NERC, 1980) were found useful for summarising the flow regime of particular twinspan groups for the unregulated sites in FBA project 103. The remaining 31 sites all classify into groups on the right hand side of the dendrogram.

Lindley Wood 2 in group J is further from the source, has a higher macrophyte cover and lower alkalinity than unregulated sites in its group. Here regulation appears to be creating conditions suitable for a fauna characteristically found in smaller streams nearer their source.

Lindley Wood 1, Thirlmere and Gouthwaite group with sites situated low down on spatey streams or near the source of small streams with stable flow regimes and which include the Cumbrian Derwent at Ouse Bridge 0.1 km below Bassenthwaite Lake. The 3 residual flow sites do not possess physical or chemical features which differentiate them from the unregulated sites in group K.

Group M contains 14 residual flow sites which are distinguished from unregulated sites in being generally closer to the source, having a steeper slope, lower discharge and higher macrophyte cover. Group M is made up of groups 56 and 57 (from division 5 of the classification, Fig. A4.3) and 13 of the residual flow sites are found in group 56. This group includes the site Cauldron Snout on the Tees which is about 0.3 km below Cow Green reservoir and also Boat of Garden on the Spey which may be affected by the lake-like section upstream at Kincraig. In group 57 Westwater, a regulated site, groups with sites which are generally low down on spatey systems or in the case of the R. Wansbeck have a lake at the source of the stream.

Group N contains 10 residual flow sites including the unregulated control site on the R. Sett. The discharge is generally lower in the regulated sites but most other physical and chemical variables are similar to those of the unregulated sites. Included in this group are Kinlochard and Aberfoyle Bridge, sites on the R. Forth system situated 3 and 2 km below Loch Chon and Loch Ard respectively. Also included in group N is Wooton Bridge on the Avonwater, again with a small lake at its source and with a base-flow index (BFI) of 0.71. It is not possible to explain the inclusion of the Hodder at Great Bridge in this group with the present data as there are no lakes or reservoirs upstream and the BFI is only 0.21.

Group O contains one regulated site, Kinder 2, which does not differ markedly in most physical characteristics from the other sites. However discharge in 10 of the 11 unregulated sites is much higher than at Kinder 2. The group contains two sites, High Stock Bridge on the Derwent and Ennerdale Bridge on the Eden which are situated 3 and 2 km downstream of Derwent Water and Ennerdale Water respectively.

Group P includes the unregulated control site on the R. Wear at Wearhead and the regulated site Boothwood. The latter site has the lowest discharge and the highest macrophyte cover (Table A4.9) in the group but cannot be distinguished from the remaining sites in the group on other physical characteristics.

Most attention however should be given to the regulated and unregulated sites in groups K, M, N, since these contain enough of each type for a fair comparison. In general, unregulated sites group with regulated sites which are flatter, at a lower altitude and located further from the source (see Table A4.9). A possible explanation could be that the combination of relatively low discharges for a large proportion of year on the steeper slopes below reservoirs produces a similar velocity environment to the more variable natural discharge on flatter slopes. This is substantiated by similar observed velocities at regulated and unregulated sites.

Table [illegible] summarises the faunal characteristics of residual flow sites within their TWINSPAN groups. Diptera are common and abundant at all sites but it is the subdominant orders which reveal the differences between groups. Ephemeroptera and Plecoptera do not feature prominently in groups 39, 44 and 50 but do so in higher numbered groups. Similarly there is a decline in both abundance and occurrence of families of Oligochaeta from group 39 to 63. Trichoptera occur widely but groups 50, 52, 56, 57 and 58 contain the highest numbers of families. Mollusca were abundant only in group 44.

4.2.5 Prediction

In the FBA 103 project (Wright et al. 1981) attempts were made to predict the TWINSPAN group membership of sites. This was achieved firstly by using the TWINSPAN key which allows new sites to be classified on the basis of their macroinvertebrate fauna and secondly with multiple discriminant analysis (MDA) which uses environmental data to produce equations to predict group membership of a new site. Both methods were applied to the 33 sites investigated in this project. The TWINSPAN key was based on the classification of 268 FBA 103 sites using the combined seasons' quantitative family level data. Similarly the MDA equations were based on environmental data collected for the 268 FBA 103 sites.

A comparison of the two methods is presented in Table A4.11. It is clear that there is very little agreement between the two sets of predictions and in 3 cases, Bottoms/Teggsnose, Scout Dike and Lindley Wood 1, the sites are placed in opposite halves of the classification. These predictions cannot however be compared with the actual TWINSPAN groupings of regulated sites since different data sets are involved.

Both key and MDA equations will only produce accurate predictions if the new sites have characteristics similar to those used to construct the key and develop the equations. The poor agreement in this area is probably due to the fact that residual flow sites do not come within the scope of the 268 site classification.

In general, predictions using the TWINSPAN key are more informative than those using MDA. For example the 3 sites Bottoms/Teggsnose, Scout Dike and Lindley Wood 1 which have been shown to be widely separated from most of the other residual flow sites both by ordination, classification and the key, are not indicated as being in any way unusual by the MDA

equations. It is likely therefore that some environmental variable or combination of variables, such as discharge pattern, sediment deposition or temperature regime, which would characterise sites with regulated flows are not being recorded or used in the derivation of the predictive equations.

4.2.6 Application of BMWP score system

The biotic score system developed by the Biological Monitoring Working Party and described and tested by Armitage et al. (1983) was applied to the 33 residual flow sites. Scores and ASPT values for separate and combined seasons' samples are presented in Table A4.12. Scores below 100 were recorded at 13, 17 and 20 sites in spring, summer and autumn samples respectively. The equivalent data for ASPTs below 6.00 were 10, 13 and 21. In the combined seasons' data set four sites, Meldon, Bottoms (Longdendale), Winscar and Boothwood had scores below 100 and 6 sites, Bottoms/Teggsnose, Bottoms (Longdendale), Scout Dike, Castleshaw, Widdop and Lindley Wood 1 had ASPT values below 6.00.

Armitage et al. (1983) have shown that there is considerable variation in achievable score and ASPT in different categories of unpolluted sites. In order to assess the meaning of these low scores and ASPT's at particular sites it is necessary to see if the values fall within the normal range observed in groups which include those sites. A TWINSPAN key derived using BMWP scores for a family level combined seasons' classification of 268 FBA 103 sites was used to predict the group membership of residual flow sites. Table A4.13 compares actual score and ASPT for the nine sites with expected values and ranges for each TWINSPAN group to which the residual flow sites key out.

At all these sites, except Lindley Wood 1, score and/or ASPTs are lower than expected for the group to which they key out. This suggests that regulation is altering the fauna by increasing the number of low scoring taxa and reducing the number of high scoring taxa as in sites with relatively high scores and low ASPTs, In the case of Meldon, Boothwood and Winscar reducing the total number of families without reducing high scoring taxa results in low scores and high ASPTs.

Armitage et al. (1983) developed multiple regression equations to predict score and ASPT from environmental data. The results of using physical and chemical data in the published equations to predict scores and ASPT of the residual flow sites are presented in Table A4.14. Predicted values for both parameters were for the most part greater than the observed values which suggests that regulation is depressing the faunal potential of the sites. Calculation of the ratio of observed/predicted scores and ASPT provides an indication of sites which may be unusual faunistically. The greatest deviations from unity are seen at Bottoms/Teggsnose, Bottoms (Longdendale) and Castleshaw for score. All these sites were identified as unusual in the initial examination of score and ASPT values.

Therefore, although the predictive methods have some use in identifying problem sites it is simpler and more informative to consider the observed scores and ASPTs and to look at these in relation to the family composition of a site. In large data sets the score system, as a summary of faunal conditions, would be useful for focussing attention on unusual sites.

4.3 Discussion

4.3.1 Scope of study

The regulated sites selected for this study include areas subject to compensation discharges where only a proportion of the natural flow (before regulation) is released to the river downstream of the dam. Within the data set of 31 regulated sites this proportion ranged from about 80% at Belmont to 3.5% at Castleshaw and covered areas in England, Scotland and Wales. In view of the decision to include a wide geographic range of sites with varied compensation flows and the limited time available, samples at increasing distance from outflows were lacking from the data set and only two controls (unregulated streams adjacent to regulated discharges) were sampled.

4.3.2 Site grouping and environmental variables

This survey has demonstrated that a range of communities occurs below reservoirs releasing water as compensation flow. However in the combined seasons' data set most of the sites fall into two closely related groups. It has not been possible to associate group membership with any one particular environmental variable or group of variables. There was no obvious relationship between discharge type or quantity and group number. For example, Gouthwaite is subject to control rules which can allow flows from the reservoir to range from 23-709 Ml/day and it occurred in the same group as Lindley Wood 1 which receives a constant discharge of 18 Ml/day.

There did appear to be a positive relationship between age of reservoir and number of families recorded. This might be expected since fauna would have had longer to colonise and adapt below older reservoirs. However there were several exceptions and more data would be required to test this hypothesis. In some of the groups of residual flow sites the regulation of the discharge appeared to alter the complement of families to a community type normally associated with conditions further downstream. The faunal communities present were not consistent with the physical characteristics of the site, that is, what in physical terms was a headwater stream had communities more normally found further downstream. This may be a consequence of the reduction in fluctuations in flow which are normally associated with hill streams.

A corollary of this is the fine sediment which covers the substratum in the majority of regulated sites. The flow fluctuations were insufficient to mobilise this material and as a result oligochaetes and chironomid larvae, which are often associated with fine sediments, were abundant. The quantities of this material did not appear to have an adverse effect on the macroinvertebrate fauna as a whole but it is possible that by altering flow and water chemistry through interstitial spaces in the substratum conditions would be unsuitable for spawning salmonids.

4.3.3 Regulated/unregulated sites

Only two unregulated control sites were sampled in the survey. In both the numbers of families recorded were the same or lower than in the adjacent regulated streams. This agrees with Ward & Stanford (1979) who found that most major taxa (with the exception of Plecoptera,

Ephemeroptera and Coleoptera) are relatively more abundant downstream of reservoirs than at nearby control sites.

At the unregulated site Wearhead a severe flood which occurred just before the autumn samples were taken resulted in a reduction in the total number of families as a result of scouring. A secondary effect of the flood was the deposition of large quantities of silty sand at the mouth of the adjacent regulated site (Burnhope) thereby changing the substratum from a cobble/boulder bottom to one where sand dominates. The constant discharge from Burnhope reservoir failed to shift this deposit by the time the autumn samples were taken.

Burnhope and Wearhead occupied different TWINSPAN groups, but Sett (unregulated) and Kinder 1 (regulated) were found in the same group. This indicates that Burnhope is more affected by regulation processes than is Kinder 1.

4.3.4 Ordination, classification and prediction

In general these procedures were useful in identifying major groupings of regulated sites. However the classification is not a rigid framework and if individual seasonal data were used in place of those from combining the seasons the group membership of sites would probably change. The advantage of using data from all seasons together is that it provides a summary of conditions for the whole year and gives a more comprehensive listing of families and hence a more valid classification.

The methods identified certain sites as being particularly unusual in that they occurred in groups well separated from other sites. The available environmental data do not explain why they were outliers. In order to explain these anomalies a larger number of sites should be investigated with more attention to the physical environment. For example no data on fine sediment deposition were used in the equations, which were formulated for unregulated sites, yet this is an important feature of streams with regulated flow. Because there were no flow records available at the majority of sampling sites, the indexing of flow conditions by compensation flow and average flow cannot take account of spillage. In addition no data, other than spot readings, are available on water temperature which is known to be a feature affected by regulation and one which may have a considerable effect on the fauna (Armitage, in press) depending on whether top or bottom water is released downstream.

Despite these deficiencies the classification procedures used in this study have revealed relationships between sites in an objective way. Explanations of why sites with apparently similar physical and chemical characteristics are not grouped together in all cases awaits more detailed study.

4.3.5 Discharge regime

The detrimental effects of flow regulation often reported in the literature were not noticeable within the range of sites examined during this survey. The effect of regulated flow would be most [illegible] at sites with a constant discharge. 15 of the 29 regulated sites [illegible] survey were subject to a constant compensation discharge, but reservoir spillage would help counteract the effects of regulation. The remaining 14 sites were subject to control rules of varying degrees of complexity. Discharge patterns were therefore not so extreme as to have an adverse effect on the fauna. Twenty-one of the 31 sites have been subject to regulated flows for greater than 50 years. This would certainly have given the benthic fauna a chance to adapt to the unnatural flow regime and its concomitant effects.

At one site large fluctuations in discharge took place but not as a regular event throughout the year. Below Thruscross reservoir on 2nd and 3rd July the flow was increased from about 45 to 363 Ml/day to accommodate a canoeing event. To compensate for water lost downstream no water was released from the reservoir on the 4th, 5th and 6th July until 1015 h when 45 Ml/day was released. Samples of macroinvertebrates collected at about 1030 h showed no signs of faunal impoverishment and contained 8 more families than did spring and autumn samples. At this site sufficient water was retained at the base of the boulders and around the dense moss growth to provide refuge areas for the fauna when no water was released from the reservoir. Repeated events of this nature would have an adverse effect on the benthos.

It should be stressed that samples for this project were taken as close as possible to the reservoir outflows in order to have data on areas likely to be most affected. It is possible but not yet demonstrated, that sites further downstream would have shown reduced effects of the regulated flow regime. While no major detrimental effects were observed using family level identifications it should not be assumed that such effects might not be demonstrated if the data had been analysed at species level. Low species diversity is a feature of regulated sites (Armitage, 1978).

4.4 Conclusion

The resilience of benthic macroinvertebrates to environmental change has implications for the recommendation of optimal management procedures. Within the range of sites examined in this study (compensation flows of between 4-60% ADF) there were no noticeable detrimental effects of regulation, using family level identification. It is of course possible with further severe reductions in flow that family richness would be lowered. However the effects of change to greater flow constancy are less easy to predict and would depend on the actual quantity of water released, but it is likely that a uniform current and bank stability would result in increases in aquatic and riparian vegetation which, in the short term, would be favourable to macroinvertebrates (Armitage, 1984). However without periodic floods interstitial spaces in the substratum would soon be clogged which would reduce the number of niches available to the benthic fauna. In addition silted-up gravel would not be a suitable substratum for the spawning and development of salmonid eggs.

Survey data, while useful for cataloguing the fauna to be found below reservoirs, cannot provide information on the rate of reduction in diversity and abundance in response to extreme discharge patterns. To obtain this it would be necessary to carry out experimental work involving test releases from reservoirs or to survey sites already subject to very low or very high constant discharges. In addition further work should include more controls and also the examination of sites at increasing distance from the reservoir outflow.

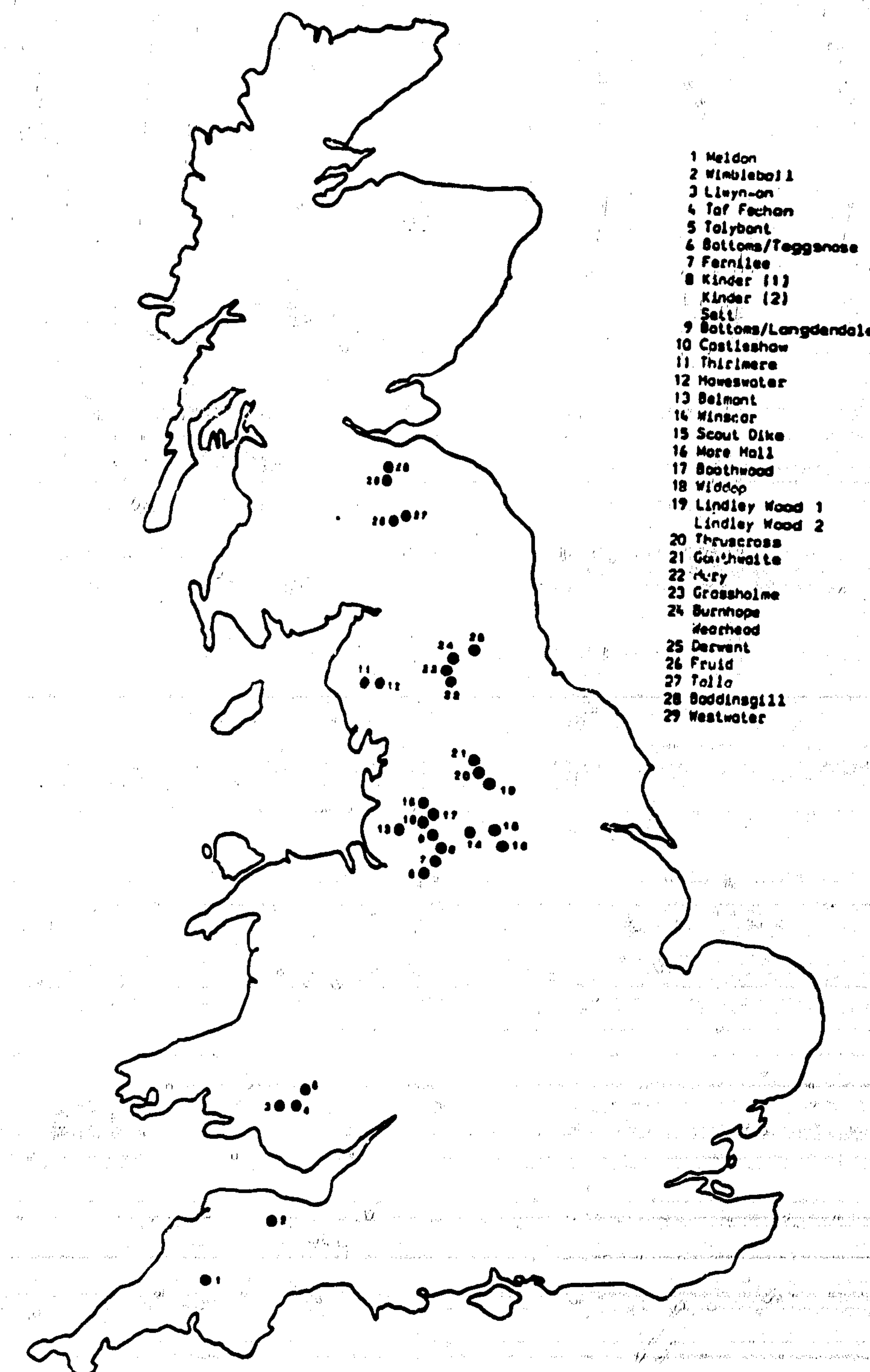

Figure A4.1 The location of the sites

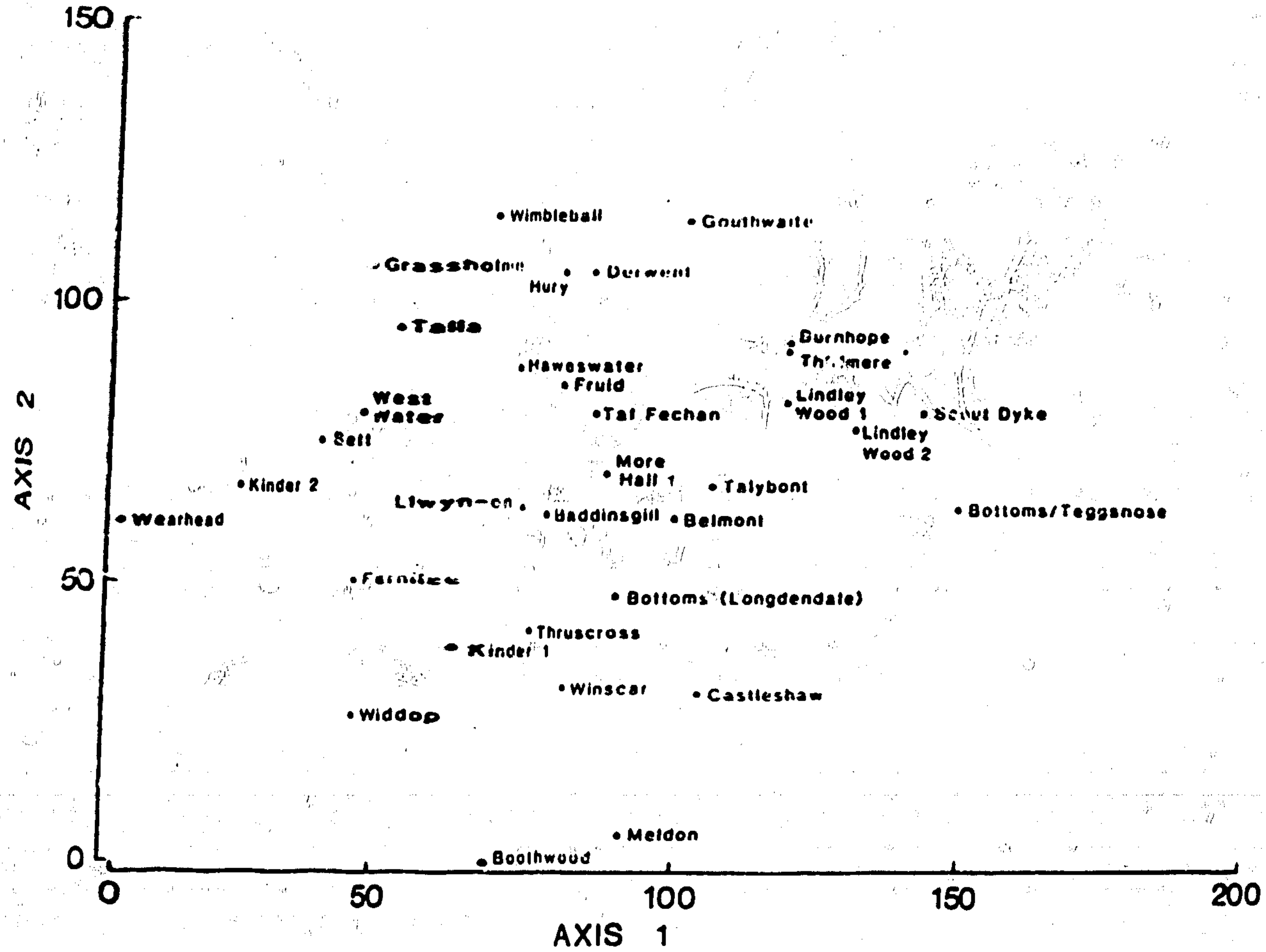

Figure A4.2 DECORANA ordination plot (Axis 1 v Axis 2) of 33 residual flow sites

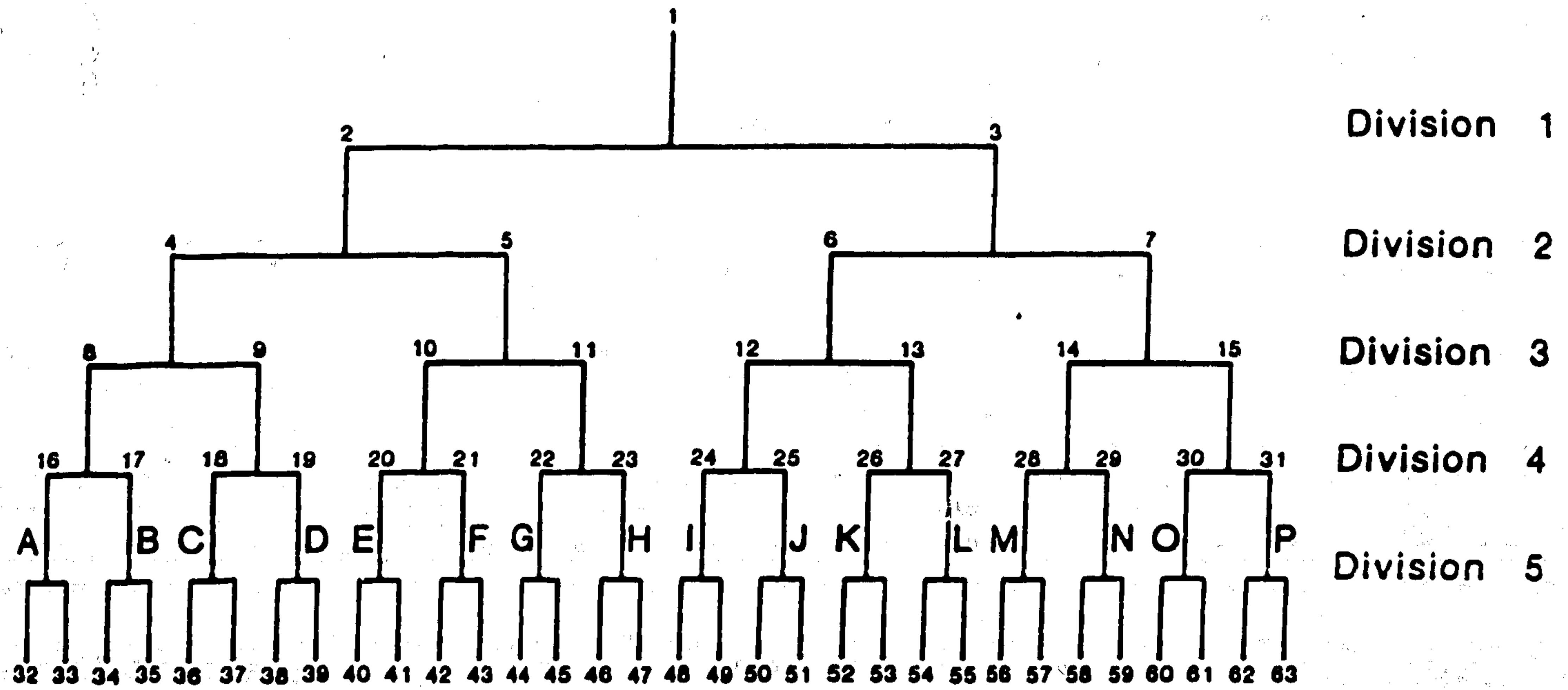

Figure A4.3 A dendrogram showing how TWINSPAN groups are developed through successive divisions 1-5. The nomenclature of the groups is indicated in the Figure.

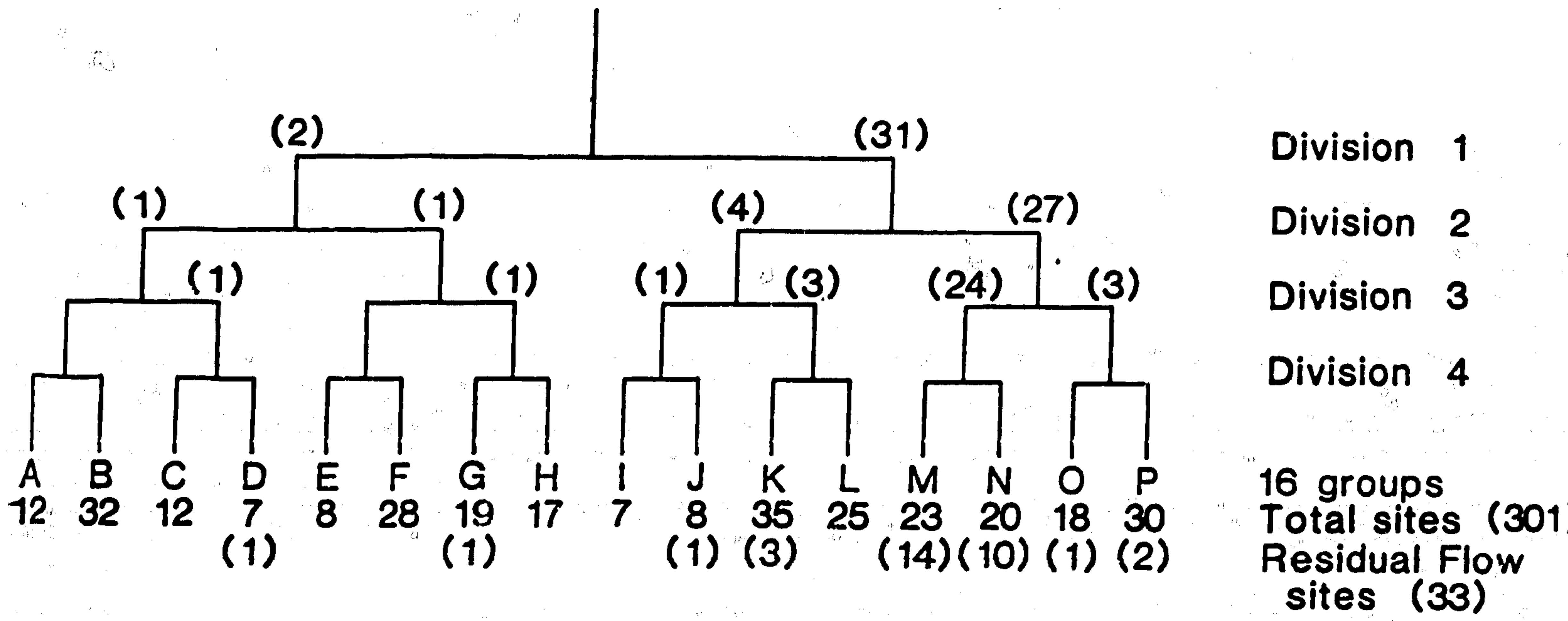

Figure A4.4 TWINSPAN classification of combined River Communities Project sites (268) and Residual Flow sites (33) based on family quantitative data from combined seasons samples. Residual flow sites are shown in parentheses.

TABLE A4.1 LIST OF SITES AND DISCHARGE CHARACTERISTICS

Site Name	River	Grid Ref.	Computer Code	Discharge characteristics: Release pattern	Flow range	Occurrence of spillage
SWWA						
Meldon	West Okement	SX 564 917	620101	CD		Sp
Wimbleball	Haddeo	SS 960 295	630101	CD+F		Sp
WWA						
Llwyn-on	Taff	SO 013 109	640101	CD		Sp
Taf Fechan	Taf Fechan	SO 059 114	650101	CD		x
Talybont	Caerfanell	SO 107 207	660101	SV	13.6–25.0	x
NWWA						
Bottoms/Teggsnose	Bollin	SJ 943 716	670101	CD		Sp
Fernilee	Goyt	SK 013 780	680101	M		Sp
Kinder (1)(a)	Kinder	SK 051 876	690101	CD		Sp
Kinder (2)(b)	Kinder	SK 047 868	690301	CD+U		Sp
Sett (unregulated)	Sett	SK 051 869	700101	U		–
Bottoms (Longdendale)	Etherow	SK 020 969	710101	M	22.7–68.2	SpSuAu
Castleshaw Lower	Tame	SD 991 090	740101	CD		x
Thirlmere	St Johns Beck	NY 310 195	880101	CD		x
Haweswater	Haweswater Beck	NY 510 159	890101	CD		x
Belmont	Belmont Brook	SD 691 155	900101	CD		x
YWA						
Winscar	Don	SE 158 024	720101	M	9.1–11.8	Sp
Scout Dike	Don	SE 238 045	720301	CR	2.7–3.9	–
[illegible] Hall (1)(c)	Barden Beck	SK 291 956	730101	CR	9.1–12.0	Sp
Booth Wood	Booth Dean Stream	SE 032 165	750101	CD		x
Widdop	Hebden Water	SD 962313	760101	M		–
Lindley Wood (1)(e)	Washburn	SE 226 482	770101	CD	18.2	Sp
Lindley Wood (2)	Washburn	SE 226 482	770102	CD		Sp
Thruscross	Washburn	SE 156 571	770301	Spill		Sp
Gouthwaite	Nidd	SE 144 679	780101	CR	22.7–70.9	–
NWA						
Hury	Balder	NY 968 195	790101	CD		SpSuAu
Grassholme	Lune	NY 960 240	800101	CD		SpAu
Burnhope	Burnhope Burn	NY 857 394	810101	CD		–
Wearhead (unregulated)(g)	Wear	NY 857 395	820101	U		–
Derwent	Derwent	NZ 033 511	830101	SV+F	22.7–25.0	Su
RB						
Fruid	Fruid Water	NT 088 206	840101	SV+F	9.0–18.0	x
Talla	Talla Water	NT 105 234	850101	SV+F	0.0–16.6	x
Baddinsgill	Baddinsgill	NT 130 550	860101	SV+F	2.3–4.0	x
West Water	West Water	NT 124 518	870101	SV+F	1.6–2.9	Sp

Key

Note: (a), (b) – u/s and d/s of Sett confluence; (c) – u/s of settling tank output
(e), (f) – u/s and d/s of fish hatchery ; (g) unregulated site on Wear u/s of confluence

Release pattern:
- CD – constant discharge
- F – freshets
- M – maintained flow
- SV – seasonally variable flow
- CR – control rules
- U – unregulated

Spillage – Occurrence on spillage on sampling occasions
- Sp – Spring
- Su – Summer
- Au – Autumn
- x – no spillage
- – – no observation

TABLE A6.2 ENVIRONMENTAL VARIABLES, ABBREVIATIONS AND BRIEF NOTES ON DATA COLLECTION PROCEDURES. (Variables whose abbreviations are prefixed L were $\log_{10}$ transformed).

Environmental variable	Abbreviation	Unit of measurement or no. categories	Footnote
Information from maps			
Distance of site from source	LKM	km	1
Slope of site	LSLOPE	m km^{-1}	1
Altitude of site	LALT	m	2
Discharge category for site	DISCH	9 categories	3
Information from survey area sheet (completed once)			
Mean channel width of survey area	LMEANW	m	4
Depth category of survey area	DEPTHC	5 categories	5
Information from sample data sheet (completed in 3 seasons)			
Date of sampling - spring	DAY 1	1-365	
Date of sampling - summer	DAY 2	1-365	
Date of sampling - autumn	DAY 3	1-365	
Mean width of water in sample area	LMWIDTH	m	7
Mean depth of water in sample area	LMDEPTH	cm	8
Maximum surface velocity of water in sample area	MAXVEL	5 categories	9
Minimum surface velocity of water in sample area	MINVEL	5 categories	10
Modal/median surface velocity of water in sample area	MEDVEL	5 categories	11
Mean substratum in sample area	MSUBST	phi	12
Minimum dominant particle size in sample area	MINDOM	7 categories	13
Maximum dominant particle size in sample area	MAXDOM	7 categories	14
Modal/Median dominant particle size in sample area	MEDDOM	7 categories	15
Maximum percentage macrophyte cover in sample area	MAXMAC	%	16
Minimum percentage macrophyte cover in sample area	MINMAC	%	17
Mean percentage macrophyte cover in sample area	MEANMAC	%	18
Chemical data provided by the water industry			
pH	pH		19
Dissolved oxygen	O2B	mg l^{-1} O	19
Total oxidised nitrogen (Nitrate + Nitrite)	LTON	mg l^{-1} N	19
Chloride	LCL	mg l^{-1} Cl	19
Dissolved orthophosphate	LORPH	mg l^{-1} P	
Total alkalinity	ALK	mg l^{-1} $CaCO_3$	19
Data from Institute of Hydrology			
Date of impoundment	DATE		
Compensation Flow	COMP	MLD	
Compensation flow as % natural mean daily flow	COMP/ADF	%	

1. Obtained from 1:250,000 O.S. maps.
2. Obtained from maps by WA/RPB biologists
3. Comp, assigned to 9 discharge categories .1 0.31 cumecs 2. 0.62, 3 1.25, 4 2.5, 5 5.0, 6 10.0, 7 20.0, 8 40.0, 9 80.0
4. Normally assessed using occurrence of bankside vegetation etc.
5. Depth in over 50% survey area; 1 25 cm, 2 50, 3 100, 4 200, 5 200.
7. Mean width from three s ampling dates.
8. Mean of nine depth readings: 1/4, 1/2 and 3/4 width x three sampling dates.

9,10,11. Maximum, minimum and modal/median categories respectively from three sampling dates. Categories: 1 10 cm sec^{-1}; 2 25; 3 50, 4 100; 5 100.

12. Mean phi values from three sampling dates weighted by % composition of the substratum in each season and based on four phi values estimated by eye: boulders/cobbles (phi-7.75); pebbles/gravel (-3.25); sand (2.0); silt/clay

13,14, 15. Minimum, maximum and modal/median categories respectively from three sampling dates.

7 phi categories:	-9	-6.5	-4.5	-2	2	6.5	9
range of phi values:	-10, -9, -8	-7,-6	-5,-4	-3,-2,-1	0,1,2,3,4	5,6,7,8	9
name of particle:	boulders	cobbles	pebbles	gravel	sand	silt	cl

16,17,18. Maximum, minimum and mean % cover respectively from three sampling dates

19. Mean of all determinations available for one year.

TABLE A6.3 SUMMARY OF MEAN VALUES OF PHYSICAL AND CHEMICAL VARIABLES RECORDED AT EACH SITE

SITE CODE	LKM	LSLOPE	LALT	DISCH	LMEANW	DEPTHC	DAY1	DAY2	DAY3	LMWIDTH	LMDEPTH	MAX	MIN	MED	MSUBST	MINDOM	MAXDOM	MEDDOM	MAC MAX	MAC MIN	MAC MEAN	PH	O2B	LTON	LCL	LORPH	ALK	DATE	COMP	COMP/ADF
620101	0.88	1.29	2.37	3	0.85	1	100	179	262	0.82	1.38	5	3	3	-6.73	-9.00	-9.00	-9.00	5	0	1.7	6.32	11.00	-0.12	1.01	-1.82	9.67	1972	7.7	8.5
630101	0.83	1.23	2.26	3	0.78	1	100	179	262	0.78	1.49	4	3	3	-5.65	-6.50	-6.50	-6.50	30	0	11.7	6.33	10.70	0.20	1.10	-1.70	27.33	1977	9.1	13.6
640101	1.01	1.06	2.37	4	1.02	2	101	180	263	1.02	1.50	5	3	4	-7.36	-9.00	-6.50	-6.50	15	0	8.3	7.63	9.70	-0.51	0.99	-1.35	45.78	1927	23.2	13.6
650101	1.01	1.18	2.47	3	1.00	2	101	180	263	1.17	1.25	4	3	4	-6.47	-6.50	-6.50	-6.50	40	10	28.3	7.85	10.60	-0.19	0.93	-1.70	76.86	1927	21.8	15.8
660101	0.95	1.49	2.20	3	0.90	2	101	180	263	0.97	1.47	3	2	3	-6.14	-6.50	-6.50	-6.50	70	0	36.7	7.45	10.80	-0.27	0.87	-1.52	43.50	1938	13.6*	13.8*
670101	0.4[illegible]	1.56	2.26	1	0.54	1	101	180	263	0.60	1.11	3	2	2	-1.74	-6.50	-6.50	-5.50	25	0	15.0	7.58	11.00	0.15	1.70	-1.00	25.00	1850	2.4	27.3
680101	0.89	1.26	2.32	1	0.85	2	102	181	264	0.81	1.51	3	3	3	-5.17	-7.75	-6.50	-6.50	65	1	38.7	7.08	11.53	-0.20	1.23	-1.48	17.43	1927	13.6	20.4
690181	0.74	1.31	2.36	1	0.65	1	102	181	264	0.62	1.09	3	3	3	-4.73	-6.50	-4.50	-6.50	5	0	2.0	6.82	11.00	-0.19	1.20	-1.30	11.00	1912	1.1	4.2
690301	0.82	1.34	2.32	1	0.74	1	102	181	264	0.74	1.41	3	3	3	-4.23	-6.50	-4.50	-6.50	10	1	4.3	6.82	11.00	-0.19	1.20	-1.30	11.00	1912	-	-
700101	0.65	1.34	2.33	1	0.65	1	102	181	264	0.62	1.32	3	1	3	-4.60	-6.50	-6.50	-6.50	0	0	0.0	6.82	11.00	-0.19	1.20	-1.30	11.00	-	-	-
710101	1.11	1.26	2.11	4	1.18	2	102	181	264	1.21	1.55	3	2	3	-4.47	-9.00	-6.50	-6.50	30	1	17.0	7.07	10.36	-0.14	1.29	-1.48	15.71	1877	22.7*	10.2*
720101	0.48	1.09	2.47	4	0.60	1	102	181	264	0.34	1.35	5	3	4	-5.20	-6.50	-4.50	-6.50	70	5	35.0	7.48	11.46	0.03	1.62	-1.30	62.98	1975	9.1*	26.1*
720301	0.89	1.13	2.31	1	0.65	1	102	181	264	0.71	1.11	4	3	3	-4.19	-6.50	-5.50	-6.50	5	0	2.0	7.35	9.88	0.51	1.73	-1.00	85.09	1924	2.7*	12.4*
730101	1.01	1.12	2.07	1	0.81	1	102	181	264	0.87	1.45	4	3	3	-5.88	-6.50	-6.50	-6.50	20	5	11.7	7.23	10.68	0.22	1.62	-1.30	57.51	1930	9.1*	20.4*
740101	0.40	1.35	2.31	1	0.40	1	103	182	264	0.39	0.89	4	4	4	-4.85	-6.50	-4.50	-6.50	35	1	13.7	7.32	11.68	-0.21	1.45	-1.40	36.11	1891	0.34*	3.1*
750101	0.44	1.54	2.33	1	0.65	1	103	182	265	0.64	1.21	5	5	5	-6.33	-6.50	-6.50	-6.50	20	1	13.7	5.56	11.00	-0.46	1.65	-1.77	3.19	1971	9.7	28.5
760101	0.93	1.33	2.36	3	0.90	1	103	182	265	0.97	1.27	4	3	4	-5.17	-7.75	-6.50	-6.50	70	30	52.3	4.53	11.00	-0.46	0.90	-1.96	0.50	1878	20.0	22.9
770101	1.32	0.94	1.83	2	1.02	1	103	182	265	0.99	1.24	3	2	2	-4.19	-9.00	-6.50	-6.50	90	10	46.7	7.80	10.34	0.11	1.33	-1.10	66.67	1875	18.2	15.3
770102	1.32	0.94	1.83	2	0.78	1	[illegible]	182	265	0.89	1.36	3	3	3	-3.94	-6.50	2.00	-6.50	75	20	38.3	7.80	10.34	0.11	1.33	-1.10	66.67	1875	18.2	15.3
770301	0.89	1.04	2.25	1	0.93	1	103	186	265	0.95	1.38	4	4	4	-6.32	-6.50	-6.50	-6.50	95	80	88.3							1967	-	-
780101	1.19	0.74	2.10	5	1.11	2	103	182	265	1.10	1.45	4	2	3	-5.20	-6.50	-6.50	-6.50	1	0	0.3	7.36	10.84	-0.24	1.11	-1.89	29.86	1901	22.7*	8.8*
790101	1.10	1.48	2.39	2	1.00	3	104	183	266	0.90	1.49	5	3	4	-5.39	-7.75	-6.50	-7.75	70	25	46.3	7.40	11.00	-0.55	0.85	-1.30	27.00	1894	15.2	16.9
800101	1.28	1.21	2.34	3	1.20	1	104	183	266	1.23	1.52	4	2	4	-6.43	-9.00	-6.50	-9.00	85	5	50.0	7.40	11.00	-0.51	0.84	-1.52	33.00	1915	28.4	12.6
810101	0.80	1.31	2.53	3	0.81	2	104	183	266	0.81	1.61	4	2	2	-3.23	-6.50	2.00	-6.50	95	0	35.0	7.39	11.00	-0.36	0.80	-1.55	23.02	1936	9.1	15.1
820181	0.90	1.14	2.53	2	0.88	1	104	183	266	0.82	1.37	4	2	4	-4.11	-6.50	-4.50	-6.50	5	0	1.7							-	-	-
830101	1.22	0.88	2.28	3	0.98	2	104	183	266	0.91	1.24	4	4	4	-5.76	-6.50	-6.50	-6.50	65	22	37.3	7.33	11.00	-0.06	1.03	-1.70	17.83	1916	22.7*	17.1*
840101	0.89	0.86	2.45	1	0.70	1	105	184	267	0.67	1.22	4	4	4	-6.09	-6.50	-5.50	-6.50	30	0	11.7	7.23	10.55	-0.37	0.86	-1.52	33.75	1968	9.0*	12.4*
850101	1.01	1.26	2.43	1	0.70	1	105	183	267	0.92	1.18	3	2	3	-6.48	-6.50	-6.50	-6.50	75	10	48.3	7.23	10.55	-0.37	0.86	-1.52	33.75	1905	0.0*	0.0*
860101	0.44	1.45	2.47	1	0.48	2	105	184	267	0.49	1.34	4	2	3	-5.85	-6.50	-6.50	-6.50	95	15	60.0	7.59	10.93	-0.12	1.00	-1.30	62.23	1930	2.3*	10.9*
870101	0.63	1.2[illegible]	2.45	1	0.44	1	105	184	267	0.48	1.26	4	3	3	-5.36	-6.50	-2.00	-6.50	70	40	53.3	7.54	10.69	0.08	1.03	-1.30	70.[illegible]9	1967	1.6*	11.8*
880101	1.12	1.20	2.23	3	0.90	1	105	185	266	0.94	1.30	3	3	3	-6.15	-6.50	-6.50	-6.50	100	5	55.0	6.25	11.00	-0.68	0.48	-2.05	6.50	1894	13.6	5.5
890101	0.98	1.09	2.31	3	0.90	2	106	185	267	0.90	1.43	3	3	3	-6.51	-6.50	-6.50	-6.50	55	20	35.0	6.8[illegible]	11.00	-0.64	0.60	-1.82	14.75	1941	21.8	12.8
900101	0.68	1.44	2.25	2	0.65	2	106	185	268	0.64	1.14	5	4	4	-5.84	-7.75	-6.50	-6.50	95	30	68.3	7.[illegible]2	10.46	-0.05	1.40	-0.72	30.00	1826	15.6	79.6

* At sites with variable compensation flow, minimum flow is recorded.

TABLE A4.4 **TEMPERATURE READINGS AT THE 33 RESIDUAL FLOW SITES OBTAINED AT THE TIME OF SAMPLING IN SPRING, SUMMER AND AUTUMN. (Missing values are indicated by -)**

Site	Temperature °C Spring	Summer	Autumn
SWWA			
Meldon	-	9.1	12.6
Wimbleball	-	11.7	14.0
WNWDA			
Llwyn-on	-	10.7	12.8
Taf-Fechan	-	11.6	12.6
Talybont	6.5	13.1	13.4
NWWA			
Bottoms/Teggsnose	6.4	13.3	12.7
Fernilee	5.2	9.0	9.1
Kinder 1	6.0	10.9	10.5
Kinder 2	6.5	12.6	10.0
Sett	6.3	12.2	9.6
Bottoms (Longdendale)	5.7	14.3	11.7
Castleshaw	5.4	13.4	11.2
Thirlmere	-	13.5	12.4
Haweswater	-	14.5	12.4
Belmont	-	21.0	11.7
YWA			
Winscar	4.6	10.4	8.9
Scout Dike	6.2	14.4	11.5
More Hall	6.1	10.2	12.5
Boothwood	4.9	7.7	11.6
Widdop	6.1	15.1	8.8
Lindley Wood 1	8.0	13.4	12.3
Lindley Wood 2	8.0	14.5	13.6
Thruscross	5.5	12.0	12.1
Gouthwaite	6.2	16.0	10.6
NWA			
Hury	4.9	13.4	11.4
Grassholme	5.1	10.6	11.8
Burnhope	5.2	12.0	12.5
Wearhead	6.6	13.6	13.4
Derwent		14.3	14.1
TRPB			
Fruid	-	13.5	11.0
Talla	-	12.8	10.1
Baddinsgill	-	10.5	10.6
Westwater	-	13.5	11.3

TABLE A4.5 **SEASONAL VARIATIONS IN THE NUMBER OF FAMILIES RECORDED AT 33 SITES**

Sites	No. of Families recorded Spring	Summer	Autumn	Combined
Meldon	7	14	9	16
Wimbleball	31	21	31	39
Llwyn-On	18	18	23	29
Taf Fechan	17	23	18	31
Talybont	26	24	26	35
Bottoms/Teggsnose	31	30	25	41
Fernilee	17	17	18	28
Kinder 1	24	24	28	36
Kinder 2	29	28	28	40
Sett	25	21	21	36
Bottoms (Longdendale)	13	22	20	30
Winscar	19	22	19	28
Scout Dike	22	21	22	33
More Hall 1	26	26	24	34
Castleshaw	19	24	24	32
Boothwood	13	12	16	18
Widdop	14	18	22	29
Lindley Wood 1	39	34	31	47
Lindley Wood 2	33	38	33	47
Thruscross	19	27	17	29
Gouthwaite	36	35	28	49
Hury	34	35	33	44
Grassholme	28	33	27	39
Burnhope	17	18	19	35
Wearhead	17	14	11	24
Derwent	28	27	26	36
Fruid	23	20	21	37
Talla	26	26	29	38
Baddinsgill	25	27	23	35
Westwater	31	36	26	43
Thirlmere	22	27	29	36
Haweswater	29	27	26	39
Belmont	24	23	19	33
Total families	63	61	61	70

TABLE A4.6 THE OCCURRENCE AND RELATIVE ABUNDANCE OF FAMILIES OF MACROINVERTEBRATES RECORDED AT 33 SITES IN SPRING, SUMMER AND AUTUMN SAMPLES. THE ABUNDANCE FIGURES ARE THE SUM OF THE VALUES RECORDED IN EACH SEASON.

	Meldon	Wimbleball	Llyn-on	Taf Fechan	Talybont	Bottoms/Teggsnose	Fernilee	Kinder 1	Kinder 2	Sett	Bottoms (Longdendale)	Winscar	Scout Dike	More Hall 1	Castleshaw	Boothwood	Widdop	Lindley Wood 1	Lindley Wood 2	Thruscross	Gouthwaite	Hury	Grassholme	Burnhope	Wearhead	Derwent	Fruid	Talla	Baddinsgill	Westwater	Thirlmere	Haweswater	Belmont	Occurrences
Spongillidae						2																												1
Hydridae														1					3								3	2			4			5
Planariidae		2			3	4	2	2						6	6		1	3	4		3		1			1		2	4	5	2	6		18
Dendrocoelidae		1																	1															2
Hydrobiidae		4				8		1			1		2	3	1			2	7															9
Lymnaeidae		4	2	2	3	6			1					1	4			2	3		1	2	2	4		3	2	3	5	1	2	3	2	22
Planorbidae			1			2																									6			3
Ancylidae		5	2	1		2	2		3	1			1	4				2	2		3	4	4	1		4	1	3	4	5		3	7	22
Sphaeriidae	1		1		1	9	2	1	2	2	5	2	5	3	2		1	2	4	3	5	4	3	3		5	1	4	3	4	9	1	8	29
Naididae	6	1	4	6	7	9	1	7	3		4	1	6	1	5	3	1	1	9	2	5	4	1	1		5	7	2	5	5	5	3	7	3[illegible]
Tubificidae						3	2	3	4	6	2	2	5	4	3	1	2	5	8	4	6	2	2	4		1	2		2	5	1	4	5	26
Enchytraeidae	5	2		1		2		2		1	1	1	2	1	2	3	2	3	2	3	2	4					2	2	1	2	2	1		24
Haplotaxidae		2																																1
Lumbriculidae	3	2	1	2	3	7	1	4	2	1	2	5	6	5	4	3	3	4	8	3	6	3	5	4		2	3	2	4	2	3	3	9	32
Lumbricidae		3		1	1	3		2	1		1	3	1	2	3			1	3	3	3	4	2	1	1	1	1	3	3	3	2	2	6	27
Glossiphoniidae						4							1					4	4		1		1	2		1	1			1	2	1		12
Erpobdellidae						2							3		1			4	6		1										2			7
Hydracarina			1	1	1		1		2	2	2	2	2		1		1	3	5		1	3		1	1	4	1		4	1	4	2	2	24
Asellidae					3	1							4								2													4
Gammaridae			6	1	6	9	6	3	1	2		5	8	7	4			6	7	9	5	6	5	2		6	9	9	8	4	5			25
Siphlonuridae										1																								1
Baetidae		7	6	5	6	5	4	9	7	5	4	8	6	7	8	4	3	4	8	3	4	7	9	2	6	5	6	8	6	9	5	5	9	32
Heptageniidae		4	3	1	2		1	2	6	7		1						1		1	3	3	7	1	5		1	4	2	6		3		21
Leptophlebiidae		1						2	1	1			1	1			1	2	1		3	4	3	1		2	3	2	1	5	1	1	1	21
Ephemerellidae		5	2	3	2	2	4	3	4	3			2	4	3			2	4	3	3	2	3		1	2	2	4	3	4	1	4	4	27
Ephemeridae		3				1															6	4	1	1		3								7
Caenidae		5	2	1		1												3	4		5	5	4	1	1	5	4	4		2		3		16
Taeniopterygidae			1		1		1	1	2																2									6
Nemouridae	2	3	4	1	2	1	5	7	4	2	4	6	1	5	3	5	7	4	4	6	2	4	2	2	5	3	1	1	3	7	4	3	4	33
Leuctridae	5	5	4	3	4	3	4	9	5	5	5	3		7	3	4	7	5	6	6	7	4	6	1	4	7	4	4	5	6	6	6	2	32
Capniidae																											1	1						3
Perlodidae	2	2	2		1	1	2	1	3	1		1				2	3			3		3	1	1	5	2	2	3	5	4	3	3		25
Perlidae									2	1													3					2						4
Chloroperlidae	1	7	2					3	3	4	1	2		2		2	2	1			2	1	2		1		3	2	4	1	[illegible]	2		23
Corixidae																												1						1
Haliplidae						1												1											1					3
Dytiscidae				1			1	2	1	2	3	2	1		1		1	1	1	1	1	3		1		1	1		1	2				2[illegible]
Gyrinidae																		1			2													2
Hydrophilidae	1								1						1			1		1	1						1			3	1			11
Helodidae																														1				1
Elminthidae		2		3			2	2	5	3	3			1		5	3	1	[illegible]	5	6	6	2	5	4	1	6	2	9		2	1		24
Sialidae						2	2	3	1	1	1	1	2	3	1		2	3	2			2	1			2						2	1	18
Rhyacophilinae	1	3	3	4	3	2		5	4	1	3	4		2	3	4	2	2	6	3	2	3	3	1	2	3	2	4	4	4		3	6	30
Glossosomatinae							1	1	2	2									1			1										1		7
Polycentropodidae	2	4	5	5	6		4	6	3	3	7	6	1	6	2	2	5	6	6	6	7	5	5	1	3	6	7	6	5	4	7	6	3	3[illegible]
Psychomyiidae										1				1				3	1		1	1	1					1		1				9
Hydropsychidae		6	6	7	8	6		4	6	3	1		6	5	2		1	3	7	1	8	7	5			3	6	3		6	5	4	3	27
Hydroptilidae		2		1	2						1		1				1	2	1			[illegible]	[illegible]	[illegible]				1	4	2	5	1		19
Limnephilidae		2		3		5	[illegible]	4	4	3		1	2	4	2	1	4	2	3	2	2	2	1		1	3	1	1	1	6	1	3	1	28
Molannidae																			1															1
Beraeidae																			1					1						1				3
Odontoceridae					1			1	3														2					3		4				6
Leptoceridae		3		3	2						3		4		1			4	3		6	4				5				1	4		2	14
Goeridae		1							1	1																				6				4
Lepidostomatidae		1			1														1	2	5	4	2								2	[illegible]		9
Brachycentridae																					1													1
Sericostomatidae		4		1	2	1		1	3				2	3				3	3	2	4	4	2	2	1	4		1			2	[illegible]		20
Tipulidae		1	1	2	2	6	1	4	1	3	3	4			6	2	1	2	4	3	2	4	3	1	2	1	2		1	4		1	5	28
Psychodidae						1										1		1			1	2		1										[illegible]
Ceratopogonidae			3	4	1	3					1				1			3	3		2	1		2						1	1		2	14
Tanypodinae	3	1	3	3	6	6	2	6	2	3	4	5	6	3	3		6	3	6	2	3	3	3	5		2	3	5	3		6	3	6	30
Diamesinae	1	5	5	6	6	5	3	2	2	1	3	3	5	1		[illegible]	1	2	4	2	3	3	4	2	4	3	5	3	7	7	2	3	4	32
Orthocladiinae	5	7	7	6	6	9	3	6	5	4	7	6	9	7	7	6	7	7	8	4	5	7	7	4	5	7	7	7	9	7	7	7	8	33
Prodiamesinae		1			5	3		2	1	3	1	1	1		2				3		1			2					1				1	15
Chironomini	1	1	3	1	4	4	1		2	3	1	2	3	4				4	5		5	6	4	2		2	5	3	3	2	7	4	2	27
Tanytarsini	4	6	6	2	7	5		3	1	5	5	6		3	6	2	2	6	9	3	5	7	5	3	1	4	2	3	7	6	7	5	5	31
Simuliidae			4		1	6	1	1	5	2	2	3	1	3	6		2	4	1		1	3	4		1		1	1		4	1		2	24
Empididae		1		2	3	6	1	2	3	1	2		1	2	5	5	3	4	4	3	3	3			3	5		2	4	3	1		2	26
Rhagionidae		1																			1	3		1		1								5
Muscidae			1		1	3						2	1					2		2	2												1	9
Total taxa	16	39	29	31	35	41	28	36	40	36	20	28	33	36	32	18	29	[illegible]7	47	2[illegible]	49	44	39	35	26	3[illegible]	3[illegible]	38	35	43	36	39	33	

TABLE A4.7 CORRELATIONS BETWEEN DECORANA SCORES AND ENVIRONMENTAL VARIABLES FOR RESIDUAL FLOW SITES (COMBINED SEASONS).

	AXIS 1	AXIS 2	AXIS 3	AXIS 4
LOG KM	0.078	0.530	0.002	-0.203
LOG SLOPE	-0.070	-0.382	0.127	0.207
LOG ALT	-0.464	-0.119	0.338	0.147
DISCH	0.1[illegible]2	0.202	0.350	0.070
LOG MEANW	-0.054	0.321	0.114	-0.086
DEPTHC	0.104	0.292	0.134	0.223
DAY1	-0.110	0.292	-0.099	-0.091
DAY2	-0.080	0.199	-0.164	-0.188
DAY3	-0.146	0.303	-0.098	-0.040
LOG MWIDTH	-0.011	0.373	0.170	-0.044
LOG MDEPTH	-0.220	0.281	0.015	0.004
MAX VEL	-0.044	-0.243	0.194	0.149
MIN VEL	0.041	-0.353	0.007	-0.154
MED VEL	-0.388	-0.298	0.233	-0.025
MSUBST	0.290	0.029	-0.282	0.386
MIN DOM	0.021	0.152	-0.070	0.050
MAX DOM	0.386	0.076	0.138	0.481
MED DOM	0.173	0.020	-0.101	0.187
MAX MAC	0.186	0.197	-0.076	-0.044
MIN MAC	-0.077	-0.03[illegible]	-0.356	-0.091
MEAN MAC	0.061	[illegible]	-0.159	-0.112
pH	0.359	0.428	0.015	0.394
O2B	-0.262	-0.264	-0.330	-0.095
LOG TON	0.361	-0.011	-0.226	0.144
LOG CL	0.273	-0.427	-0.284	0.213
LOG ORPH	0.258	-0.017	-0.184	0.388
ALK	0.353	0.216	0.001	0.219
DATE	0.195	0.375	-0.067	-0.048
COMP	0.032	0.025	0.013	0.083
COMP/ADF	0.182	-0.152	-0.111	0.156

TABLE A4.8 TWINSPAN ANALYSIS OF COMBINED SEASONS FAMILY QUANTITATIVE DATA FROM 301 SITES (268 RIVER COMMUNITIES PROJECT SITES + 33 RESIDUAL FLOW SITES). Only groups containing residual flow sites (in upper case) are listed. Also shown are the numbers of families recorded from each site (N). (* = sites below reservoirs; # = sites below lakes)

Group 39 contains 3 members		N
Wansbeck	Bothal	40
Spey	Kincraig	34
R DON	SCOUT DIKE*	33

Group 44 contains 4 members		
R. Rother (Sussex)	Durford Bridge	50
Great Eau	Swaby	40
Great Eau	Bellau	42
R. BOLLIN	BOTTOMS/TEGGSNOSE*	41

Group 5[illegible] contains 3 members		
Gwendraeth Fach	Carn-Lwyd	54
Great Eau	Ruckland	42
R. WASHBURN	LINDLEY WOOD 2*	47

Group 52 contains 12 members		
R. Dudwell	Burwash Weald	48
R. Rother	Etchingham	47
R. Tillingbourne	Wotton	45
R. Wey	Eashing	39
R. Derwent (NWWA)	Ouse Bridge #	40
R. Derwent (YWA)	Langdale End	44
R. Swale	Topcliffe	51
R. Wansbeck	Mitford Gauging Station	48
R. Forth	Parks of Garden	51
R. WASHBURN	LINDLEY WOOD 1	47
R. NIDD	COUTHWAITE	49
ST JOHNS BECK	THIRLMERE	36

Group 56 contains 15 members		
R. Tees	Cauldron Snout*	34
R. Spey	Boat of Garten	45
R. HADDEO	WIMBLEBALL*	29
R. TAFF	LLWYN-ON*	29
R. TAF FECHAN	TAF FECHAN*	31
R. CAERFANELL	TALYBONT*	35
R. BALDER	HURY*	44
R. LUNE	GRASSHOLME*	39
BURNHOPE BURN	BURNHOPE*	35
R. DERWENT	DERWENT*	36
FRUID WATER	FRUID*	37
TALLA WATER	TALLA*	38
R. BADDINSGILL	BADDINSGILL*	35
HAWESWATER BECK	HAWESWATER*	39
BELMONT BROOK	BELMONT*	33

Group 57 contains 8 members		
R. Ribble	Horton	37
R. Tees	Over Dinsdale	37
R. Tyne (NWA)	Wylam	39
R. Wansbeck	Kirk Whelpington#	44
R. Wansbeck	Meldon	42
R. Teith	Bridge of Teith, Doune	39
R. Stinchar	Ballantrae	37
WESTWATER	WESTWATER*	43

Group 58 contains 16 members		NR.
Avonwater	Wooton Bridge	43
R. Hodder	Cross of Greet Bridge	23
R. Esk	Westerdale	31
R. Esk	Castleton	30
Water of Chon	Kinlochard	26
R. Forth	Aberfoyle Bridge#	46
R. WEST OKEMENT	MELDON*	16
R. GOYT	FERNILEE*	28
R. KINDER	KINDER 1*	36
R. SETT	SETT	36
R. ETHEROW	BOTTOMS (LONGDENDALE)*	30
R. DON	WINSCAR	28
EDEN BECK	MORE HALL*	34
R. TAME	CASTLESHAW	32
HEBDEN WATER	WIDDOP*	29
R. WASHBURN	THRUSCROSS*	29

Group 60 contains 12 members		
R. Camel	Tuckingmill	38
R. Exe	Edbrooke	42
R. Avill	Wheddon Cross	40
R. Teifi (Tyfi)	Strata Florida	41
R. Hodder	D/S Langden Beck	44
R. Dane	Hug Bridge	47
R. Derwent (NWWA)	High Stock Bridge#	44
R. Ehen	Ennerdale Bridge#	36
R. Teith	Laighlands	37
R. Dee	D/S Aboyne	49
R. Dee	D/S Banchory	38
R. KINDER	KINDER 2*	40

Group 63 contains 13 members		
Gayle Beck	Cam End	36
R. Swale	Keld	29
R. Tees	Moorhouse	32
R. Tees	Dent Bank	30
South Tyne	Dipper Bridge	29
South Tyne	Alston	28
South Tyne	D/S Knaresdale	27
South Tyne	Featherstone	28
R. Dee	Linn of Dee	23
R. Dee	Braemar	33
R. Spey	Garva Bridge	29
BOOTHDEAN STREAM	BOOTHWOOD*	18
R. WEAR	WEARHEAD	24

TABLE A4.9 THE MEAN AND VARIANCE OF 9 ENVIRONMENTAL VARIABLES FOR UNREGULATED(U) AND REGULATED (R) SITES WITHIN TWINSPAN GROUPS GENERATED FROM A COMBINED DATA SET INCLUDING 268 FBA PROJECT 103 SITES AND THE 33 RESIDUAL FLOW SITES.

	n	L.Km Mean	L.Km Var.	L.Slope Mean	L.Slope Var.	L.Alt. Mean	L.Alt. Var.	Discharge Mean	Discharge Var.	LM Width Mean	LM Width Var.	LM Depth Mean	LM Depth Var.	Med. Vel. Mean	Med. Vel. Var.	MSubst. Mean	MSubst. Var.	Mean Mac. Mean	Mean Mac. Var.
Group 39																			
U	2	1.66	0.001	0.24	0.06	1.67	0.45	6.0	1.0	1.60	0.16	2.03	0.07	2.0	0	1.20	9.55	10.0	100.0
R	1	0.88	-	1.15	-	2.31	-	1.0	-	0.70	-	1.11	-	3.0	-	-4.19	-	2.0	-
Group 44																			
U	3	0.95	0.02	0.31	0.15	1.44	0.03	2.0	0.67	0.69	0.09	1.44	0.05	4.0	0.67	-2.25	9.83	36.0	672.0
R	1	0.36	-	1.56	-	2.26	-	1.0	-	0.60	-	1.11	-	2.0	-	-1.74	-	15.0	-
Group 50																			
U	2	0.5	0.04	1.00	0.09	1.87	0.02	1.0	0	0.57	0.07	1.06	0.05	2.5	0.25	-4.47	2.10	2.0	4.0
R	1	1.32	-	0.95	-	1.83	-	2.0	-	0.90	-	1.36	-	3	-	-3.94	-	38	-
Group 52																			
U	9	1.25	0.17	0.19	0.34	1.59	0.11	4.22	5.06	0.99	0.15	1.40	0.05	3.44	0.47	-1.93	13.29	38.11	420.99
R	3	1.20	0.01	0.98	0.03	2.05	0.03	3.33	1.56	0.99	0.01	1.37	0.004	3.0	0	-5.10	0.82	31.1	522.49
Group 56																			
U	1	1.82	-	-0.04	-	2.30	-	8.0	-	1.65	-	1.80	-	4.0	-	-6.40	-	1.3	-
R	13	0.94	0.04	1.22	0.04	2.37	0.009	2.85	3.05	0.87	0.04	1.46	0.10	4.0	3.38	-5.94	0.85	36.77	313.87
Group 57																			
U	7	1.48	0.20	0.54	0.12	1.50	0.38	6.14	4.98	1.29	0.13	1.48	0.05	3.71	1.63	-5.18	2.30	11.76	146.07
R	1	0.60	-	1.23	-	2.45	-	1.0	-	0.48	-	1.26	-	3.0	-	-5.36	-	53.0	-
Group 58																			
U	6	0.81	0.07	0.78	0.18	1.89	0.15	2.67	1.56	0.80	0.07	1.28	0.02	3.33	1.22	-5.19	2.98	8.55	52.75
R	9	0.93	0.08	1.34	0.09	2.18	0.09	2.1	1.65	0.76	0.07	1.32	0.04	3.44	0.25	-5.39	0.52	28.93	704.57
Group 60																			
U	11	1.21	0.28	0.64	0.18	2.02	0.05	5.18	6.51	1.06	0.19	1.43	0.10	4.18	0.33	-5.98	0.85	3.88	22.61
R	1	0.85	-	1.34	-	2.32	-	1.0	-	0.78	-	1.41	-	3.0	-	-4.23	-	4.3	-
Group 63																			
U	11	1.04	0.14	0.99	0.13	2.47	0.03	5.0	1.64	1.14	0.17	1.39	0.02	3.73	0.20	-6.71	0.54	0.94	1.09
R	1	0.44	-	1.54	-	2.33	-	1.0	-	0.64	-	1.21	-	5.0	-	-6.33	-	13.7	-

TABLE A4.10 **FAUNAL COMPOSITION OF RESIDUAL FLOW SITES WITHIN TWINSPAN GROUPS. Major taxonomic groups are ranked in order of abundance based on the original log categories. The number of families within each major taxonomic group is also presented. [Rank 1 means most abundant organisms in TWINSPAN group eg. Trichoptera is most abundant in group 60].**

Major taxonomic groups	Rank relative abundance									Families per group								
	39	44	50	52	56	57	58	60	63	39	44	50	52	56	57	58	60	63
Mollusca	6	2	5	6	6	6	6	7	7	3	5	4	5	5	3	4	3	–
Oligochaeta	2	3	3	3	4	4	4	5	5	5	5	5	5	6	5	5	4	5
Hirudinea	7	7	6	9	9	8	9	9	7	2	2	2	2	1	1	1	–	–
Crustacea	4	5	7	7	7	7	8	8	7	2	2	1	2	2	1	1	1	–
Ephemeroptera	5	6	4	4	3	3	5	4	3	3	4	4	6	6	5	4	4	4
Plecoptera	8	8	6	5	5	5	3	3	2	1	3	2	4	6	4	6	6	5
Coleoptera	8	9	8	8	8	5	7	6	6	1	1	2	5	4	4	3	3	1
Trichoptera	3	4	2	2	2	2	2	1	4	6	4	12	10	13	10	12	8	6
Diptera	1	1	1	1	1	1	1	2	1	8	12	10	13	13	8	11	9	7

TABLE A4.11 **PREDICTED GROUP MEMBERSHIP (DIVISION 5) OF RESIDUAL FLOW SITES BASED ON MDA EQUATIONS AND TWINSPAN KEY DERIVED FROM 268 UNREGULATED SITES IN FBA103 STUDY**

Site	MDA	KEY
Meldon	59	62
Wimbleball	63	59
Llwyn-on	61	56
Taf-Fechan	58	62
Talybont	62	63
Bottoms/Teggsnose	56	40
Fernilee	58	63
Kinder (1)	59	58
Kinder (2)	57	58
Sett	58	63
Bottoms (Longdendale)	60	62
Winscar	50	62
Scout Dike	63	58
More Hall (1)	57	54
Castleshaw	62	56
Boothwood	62	62
Widdop	62	62
Lindley Wood (1)	50	42
Lindley Wood (2)	50	52
Thruscross	54	63
Gouthwaite	60	50
Grassholme	61	49
Burnhope	58	50
[illegible]head	57	62
Derwent	59	60
Fruid	58	63
Talla	58	56
Baddinsgill	62	48
Westwater	54	58
Thirlmere	62	48
Haweswater	62	58
Belmont	62	60

TABLE A4.12 BMWP SCORES (S) AND AVERAGE SCORE PER TAXON (A) AT RESIDUAL FLOW SITES FOR SPRING, SUMMER, AUTUMN AND COMBINED SEASONS SAMPLES. MEAN VALUES FOR S AND A ARE ALSO SHOWN.

	Spring		Summer		Autumn		Combined	
	S	A	S	A	S	A	S	A
[illegible]tor	30	6.00	62	6.20	20	5.00	62	6.20
[illegible]eball	170	6.80	131	6.89	137	6.52	195	6.96
Llwyn-on	85	6.85	85	6.54	79	5.27	126	6.30
Taf Fechan	63	5.25	91	[illegible]	93	6.20	133	6.20
Talybont	105	6.18	99	6.19	104	5.78	154	6.70
Bottoms/Teggsnose	83	4.88	100	5.26	68	4.25	142	5.46
Fernilee	100	6.25	68	5.67	77	5.50	124	6.20
Kinder 1	113	5.95	98	6.13	126	6.00	166	6.64
Kinder 2	[illegible]	6.95	129	6.79	152	6.61	193	6.86
Sett	148	6.73	86	6.14	83	5.93	172	6.88
Bottoms (Longdendale)	57	5.70	68	5.23	77	5.50	94	5.53
Winscar	77	5.92	64	5.82	66	5.50	98	6.13
Scout Dike	70	4.67	74	4.93	69	5.31	115	5.48
More Hall 1	110	5.79	115	5.75	90	5.63	138	6.00
Castleshaw	54	4.50	89	4.93	79	4.94	112	5.33
Boothwood	56	6.22	48	6.00	60	6.00	70	6.36
Widdop	66	6.00	70	5.83	95	5.94	118	5.90
Lindley Wood 1	168	[illegible]	133	5.54	124	5.90	197	5.97
Lindley Wood 2	133	5.54	145	5.80	131	5.70	197	6.16
Thruscross	100	6.67	114	6.33	67	5.58	129	6.45
Gouthwaite	[illegible]	6.46	177	6.56	120	6.32	212	6.42
Hury	[illegible]	7.00	165	6.60	153	6.38	198	6.83
Grassholme	149	6.48	175	7.00	138	6.27	211	6.81
Burnhope	69	5.75	69	5.75	58	4.83	147	6.39
Wearhead	93	6.64	85	7.08	50	6.25	133	7.00
Derwent	[illegible]	6.33	127	6.05	129	6.14	162	6.43
Fruid	111	6.94	75	5.77	75	5.00	164	6.31
Talla	148	6.73	120	6.32	138	6.57	194	6.93
Baddinsgill	118	6.21	112	6.22	82	5.47	154	6.42
Westwater	160	6.67	172	6.37	130	6.50	212	6.63
Thirlmere	116	6.44	110	6.11	98	5.44	145	6.30
Haweswater	[illegible]	6.41	127	6.68	119	5.67	183	6.31
Belmont	95	5.94	58	5.27	71	5.46	126	6.30
[illegible]	109	6.15	[illegible]	[illegible]	96	5.74	151	[illegible]

TABLE A4.13 A COMPARISON OF OBSERVED SCORE (S) AND ASPT (A) FOR 9 SITES, WITH EXPECTED VALUES AND 10TH AND 90TH PERCENTILES FOR EACH PREDICTED TWINSPAN GROUP (T) BASED ON BMWP SCORES TO WHICH THE SITES KEY OUT

	Observed			Expected	
	S	A	T	S	A
Scout Dike	115	5.48	13	190 (140-231)	6.07 (5.6-6.5)
Bottoms/Teggsnose	142	5.46	13	190 (140-231)	6.07 (5.6-6.5)
Lindley Wood (1)	197	5.97	13	190 (140-231)	6.07 (5.6-6.5)
Castleshaw	112	5.33	14	183 (148-219)	6.43 (6.1-[illegible])
Meldon	62	5.20	15	149 (106-184)	6.65 (6.2-7.1)
Bottoms (Longdendale)	94	5.53	15	149 (106-184)	6.65 (6.2-7.1)
Winscar	98	[illegible]	15	149 (106-184)	6.65 (6.2-7.1)
Widdop	118	5.90	15	149 (106-184)	6.65 (6.2-7.1)
Boothwood	70	6.36	15	149 (106-184)	6.65 (6.2-7.1)

TABLE A4.14 THE OBSERVED AND PREDICTED SCORES AND ASPT X 100 FOR COMBINED SEASONS DATA. The ratio of observed/predicted values is also shown. Predicted values are calculated using published equations based on physical and chemical data (*no chemical data available).

	SCORE			ASPT		
	O	P	O/P	O	P	O/P
Meldon	62	180	0.34	620	672	0.92
Wimbleball	195	175	1.11	696	633	1.10
Llwyn-on	126	185	0.68	630	701	0.90
Taf Fechan	133	201	0.66	633	693	0.91
Talybont	154	195	0.79	670	697	0.96
Bottoms/Teggsnose	142	168	0.84	546	626	0.87
Fernilee	124	178	0.70	620	647	0.96
Kinder (1)	166	175	0.95	664	638	1.04
Kinder (2)	192	178	1.08	686	640	1.07
Sett	172	160	1.03	688	638	1.08
Bottoms (Longdendale)	94	173	0.54	553	648	0.85
Winscar	98	155	0.63	613	613	1.00
Scout Dike	115	157	0.73	548	585	0.94
More Hall (1)	138	158	0.87	600	606	0.99
Castleshaw	112	174	0.64	533	624	0.85
Boothwood	70	114	0.61	636	549	1.16
Widdop	118	135	0.87	590	575	1.03
Lindley Wood (1)	197	193	1.02	597	654	0.91
Lindley Wood (2)	197	205	0.96	616	640	0.96
Thruscross	129	*	*	645	*	*
Gouthwaite	212	184	1.15	642	673	0.95
Hury	198	211	0.94	583	726	0.94
Grassholme	211	199	1.06	681	712	0.96
Burnhope	147	207	0.71	639	726	0.88
Wearhead	133	*	*	700	*	*
Derwent	162	214	0.76	623	676	0.92
Fruid	164	201	0.82	631	675	0.93
Talla	194	186	1.04	693	681	1.02
Baddinsgill	154	189	0.81	642	684	0.94
Westwater	212	206	1.03	663	669	0.99
Thirlmere	145	196	0.74	630	689	0.91
Haweswater	183	203	0.90	631	697	0.91
Belmont	126	183	0.69	630	647	0.97

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APPENDIX A5. AN ANALYSIS OF FISH TRAP DATA FROM CARL BECK, TEESDALE

5.1 Introduction

A fish trap was installed in Carl Beck (Teesdale) by the Freshwater Biological Association to assess the timing and numbers of brown trout (Salmo trutta L.) migrating upstream to spawn. The trap was in operation from September 1978 to June 1981, inspected approximately every 24 hours at around 0900 GMT, and observations made regarding the size, age, sex and numbers of [illegible] caught. Most of the fish caught [illegible] sexually mature brown trout and [illegible] immature trout or other fish were [illegible] cluded from the analysis. In association with this a 'River Level Recorder' was set up to monitor levels in the beck.

5.2 Analysis

[illegible] catches of mature brown trout for the three years of operation at Carl Beck [illegible] presented in Figure A5.1. Although some migration takes place during September and December, Oct[illegible] and November are the months during [illegible] most trout migrate to [illegible] areas. In fact 92% of the trout migrating upstream did so [illegible]

It is known that [illegible] stimulated into migration by spates, whether it [illegible] mical content, increase in flow or a combination [illegible] to establish whether brown trout also respond [illegible] ean flows for the period of migration duri[illegible] the number of fish moving upstream (see Fi[illegible] to be a temporal coincidence between sp[illegible] where these floods occur between late September [illegible] ber. Events occurring at other times appear to be outside the spawn[illegible] season and induce little response. Similarly during 1978 and 1980 spates occurring within the spawning season stimulated trout into moving upstream.

To identify those spates which produce preferred conditions for upstream migration the maximum flow for each day within the spawning season was grouped according to size and plotted against the total number of fish moving within each range of flows (see Figure A5.3). The graph shows that most fish (71.5%) were caught on those days when the maximum flow recorded fell in the range 0 to 0.32 cumecs (640% ADF+) with the greatest number of fish migrating on those days with a maximum flow between 0.04 (80% ADF) and 0.08 cumecs (160% ADF). Flows in excess of 0.32 cumecs (640% ADF) appear to be related to lower numbers of trout moving.

Whilst these figures give some indication as to the preferred flow range there may be more days in one class than another, so the chance of migration is higher in any case. To estimate the probability of migration occurring, those days when no fish were caught were compared with those days when at least one fish was caught (see Figure A5.4). For those days with a maximum flow less than 0.04 cumecs (80% ADF) there are more occurrences of fish not moving. However, for those days with a maximum discharge between 0.05 (ADF) and 0.06 cumecs (120% ADF) at least one fish has migrated upstream on each and every day, as it did on those days with maximum flows between 0.06 (120% ADF) and 0.07 (140% ADF). In fact for the majority of days with a maximum discharge in the range 0.04 (80% ADF) to 0.28 cumecs (560% ADF) trout have been recorded moving upstream. Thus, you

+Average daily flow calculated from flow record.

could predict that for a spate which reached a peak between 80% ADF and 560% ADF then the likelihood of fish migrating upstream during this period is very high.

5.3 Conclusion

The data indicates a correlation between spates and the upstream migration of mature brown trout where these spates occur during the spawning season. As the precise time at which migration took place is not known, only that movement has occurred since the last trap inspection, it is difficult to relate migration to an exact discharge. However, it is possible to relate migration to the range of flows which occurred during that period. Indeed it appears that the preferred spates are those greater than 80% ADF but not larger than 700% ADF.

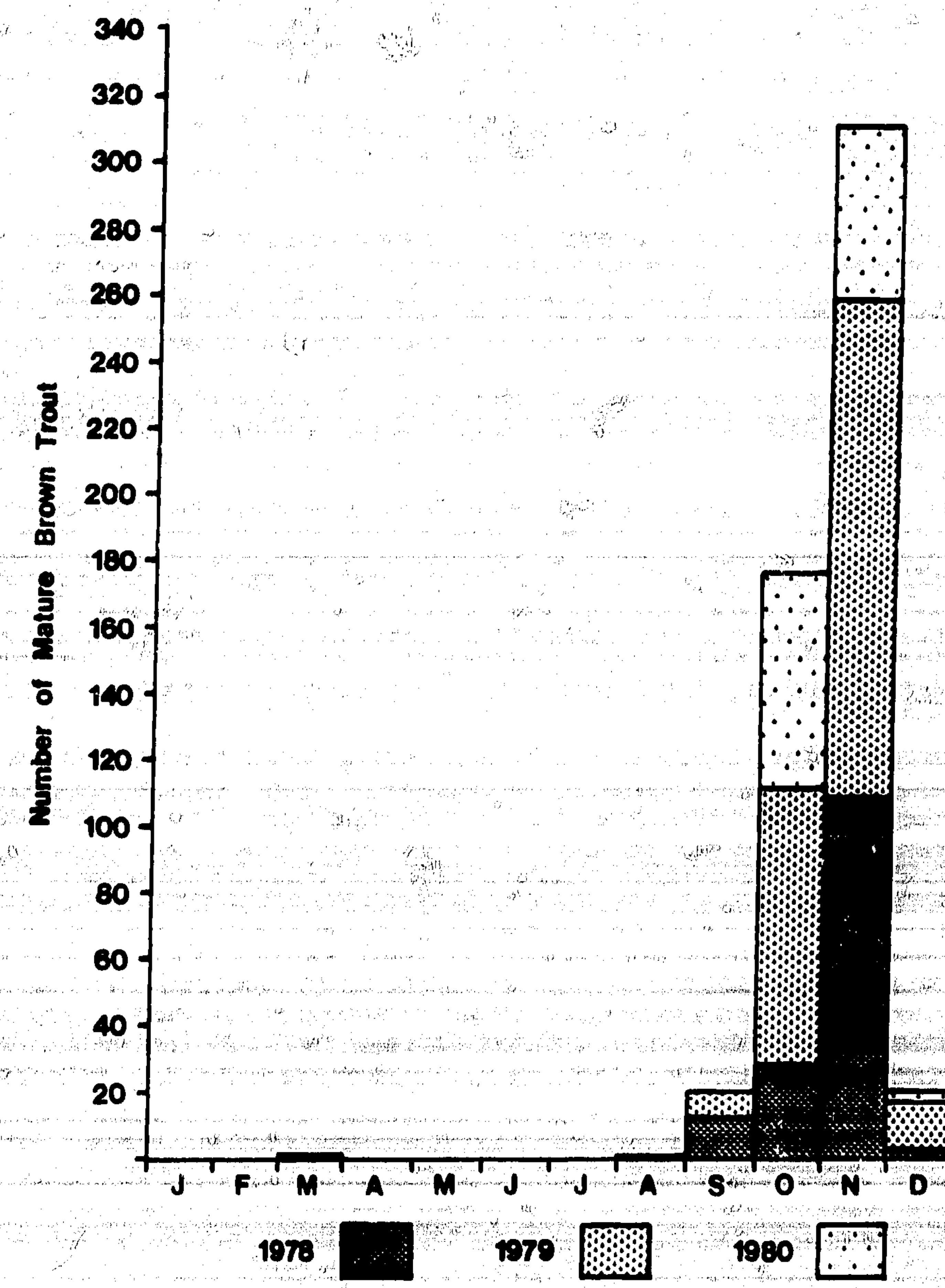

Figure A5.1 Catches of mature brown trout at Carl Beck.

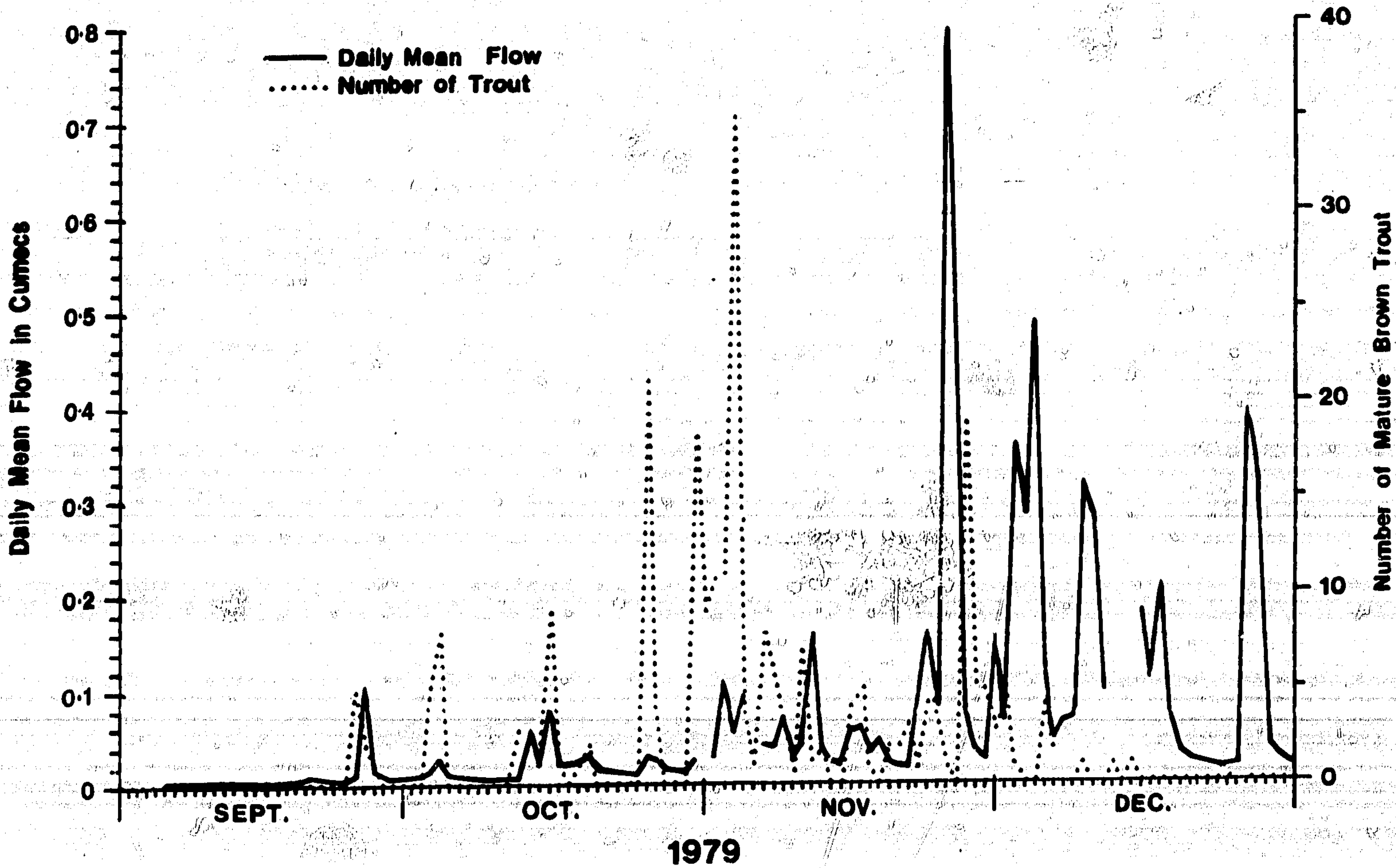

Figure A5.2 Hydrograph and upstream migration of mature brown trout during 1979

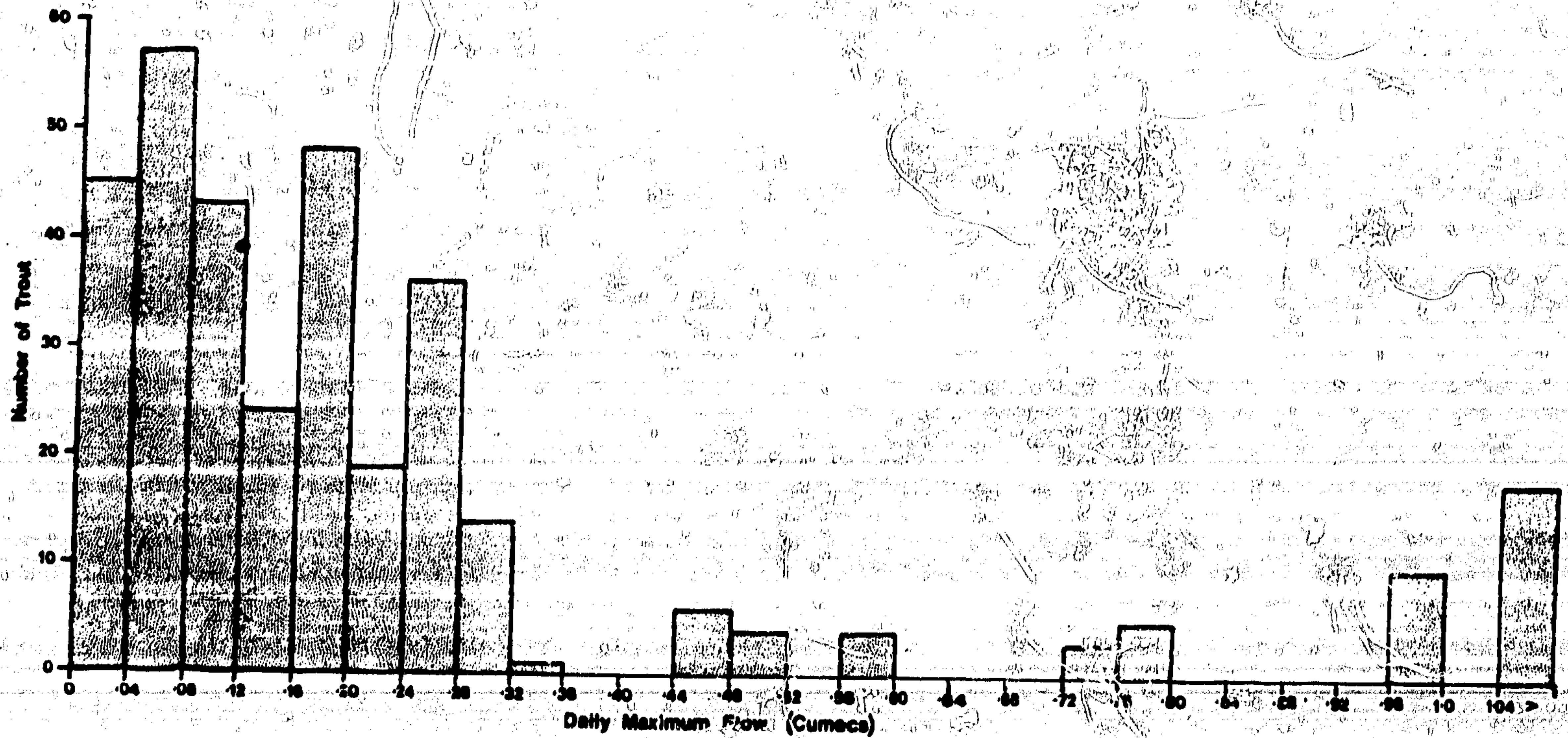

Figure [illegible] ~ferred flow range for migrating brown trout.

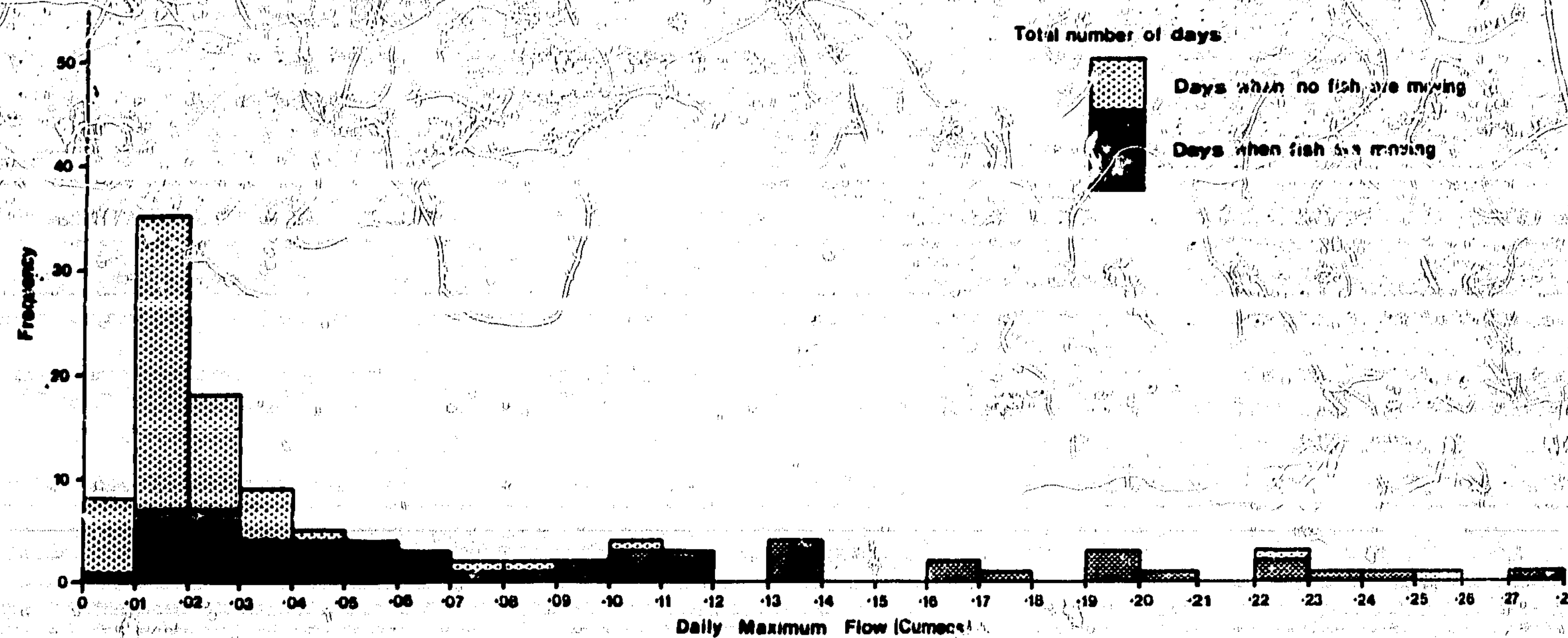

Figure A5.4 Frequency of migration

APPENDIX A6 SEASONAL FLOW DURATION CURVE ESTIMATION MANUAL

This Appendix presents the results of a study of the seasonal variation of flow duration curves in the form of a self contained estimation manual. The manual enables monthly and seasonal flow duration curves to be calculated using mean daily flow data or estimated at ungauged sites using the characteristics of the catchment area. The Appendix adopts the same style as earlier reports in the Low Flow Study Series and for this reason the convention of prefixing figures and tables by the letter A has been omitted from this Appendix.

APPENDIX A6

LOW FLOW STUDIES

Report No 2.4

Seasonal flow duration curve estimation manual

PREFACE

This report describes the procedure for estimation of monthly and seasonal flow duration curves for both gauged and ungauged catchments. It forms one of a series of reports which document the work of the Low Flow Study carried out at the Institute of Hydrology and funded by the Department of the Environment.

The complete series of reports is as follows:

Report No 1	*Research Report*
Report No 2	*Manuals for estimating low flow measures at gauged or ungauged sites*
Report No 3	*A manual describing the techniques for extracting catchment characteristics*

The first report outlines the scope of the Low Flow Study; it describes the analysis of the flow data, the derivation of the relationship between low flows and catchment characteristics and summarises the estimation technique. The second report series takes the form of calculation sheets which describe the underlying principles of each low flow measure and enable the user to estimate them from flow data or catchment characteristics; procedures are also given for incorporating local gauged data at various stages in the estimation technique. Report No 3 describes the techniques for calculating catchment characteristics.

CONTENTS

ILLUSTRATIONS

FIGURES

TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

ADF	average discharge (cumecs)
MRV	monthly runoff volume as percentage of annual runoff volume
AMD	average monthly discharge (cumecs)
BFI	base flow index
SAAR	standard period (1941-1970) annual average rainfall (mm)
Q95(10)	10 day average flow exceeded by 95% of 10 day average discharges (expressed as a percentage of ADF)
Q95	flow exceeded 95% of the time (expressed as a percent of AMD) - this always refers to a specific calendar month
Q5	flow exceeded 5% of the time (expressed as a percent of AMD) - this always refers to a specific calendar month

1. INTRODUCTION

1.1 OUTLINE AND SUMMARY

Seasonal flow duration curves illustrate, for any month (e.g. all Octobers) or group of months (e.g. all January–June periods), the relationship between discharge and the percentage of time that discharge is exceeded. They have application where the frequency distribution of flows is required for a particular month or group of months which is critical in a hydrological design problem. Examples are found in the licensing of river abstractions, in the estimation of sewage effluent dilution and in assessing the compensation flows needed below reservoirs – in each case different standards may be applied to different times of the year.

Chapter 1 of this manual contains an outline of how monthly and seasonal flow duration curves are constructed and how they can be interpreted. It includes an insight into the factors affecting the shape of the curve and explains how the curves may be expressed either in discharge terms or alternatively as a percentage of the average discharge of the particular month or season. It concludes with an outline of the estimation strategy dependent upon requirement and data availability.

Chapter 2 explains how to derive a monthly or seasonal curve using flow data from a gauged catchment, and Chapter 3 details methods of deriving curves at ungauged sites. Chapter 4 illustrates how best to make use of local data.

This manual illustrates the estimation techniques by making use of a worked example, the River Pang at Pangbourne. Seasonal flow duration curves are constructed from gauged data collected at this site and the methods suggested for estimating seasonal curves at ungauged sites are also detailed for the same catchment. Information on three other catchments which can be used to practise the recommended techniques is given. Necessary information on all four catchments will be found in section 1.1 of Low Flow Studies Report 2.1. As far as is practical the worked example will be found on right-hand pages whilst the catchments included for practice will be found in italic type on left-hand pages.

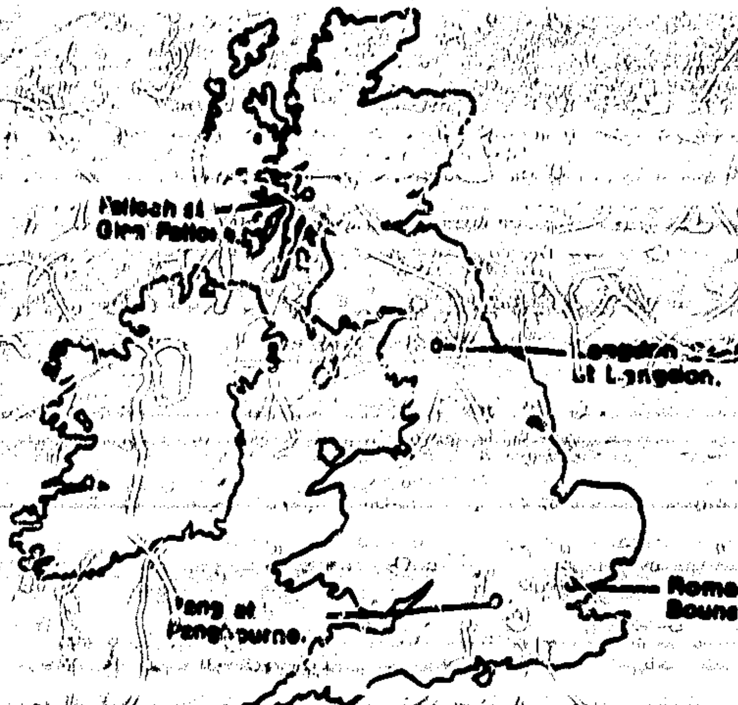

FIGURE 1.1 LOCATION OF ALL THE EXAMPLE CATCHMENTS

1.2 DERIVATION OF THE CALENDAR MONTH FLOW DURATION CURVE

A flow duration curve derived for a particular month is obtained by using all data in that month (e.g. October) from each year of record available. Figure 1.2 illustrates in diagrammatic form the data used in the creation of a monthly flow duration curve for October from a five year period of data.

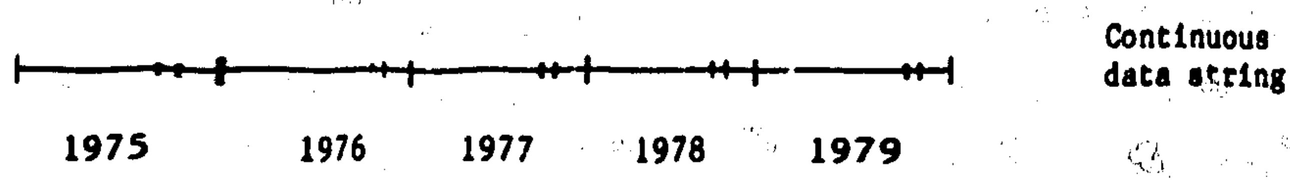

FIGURE 1.2 **DATA SELECTION IN THE DERIVATION OF A MONTHLY FLOW DURATION CURVE**

A monthly curve can be constructed from any length of record and will validly represent flow conditions for that particular period. However if the object is to represent long term average seasonal flow conditions, then of course the use of long records will reduce sampling variability.

Figure 1.3 is an example of a monthly flow duration curve. It has been derived from data gauged on the river Pang at Pangbourne during October. Fifteen years of record are available at this location which together give rise to 15 x 31 (i.e. 465) days of daily flow data which have been used in the derivation of this October curve. It can be seen that, for example, for five percent of the time (i.e. five out of every one hundred October days) the flow was greater than 0.65 cumecs or, again, that the flow exceeded on 95 percent of October days is 0.22 cumecs.

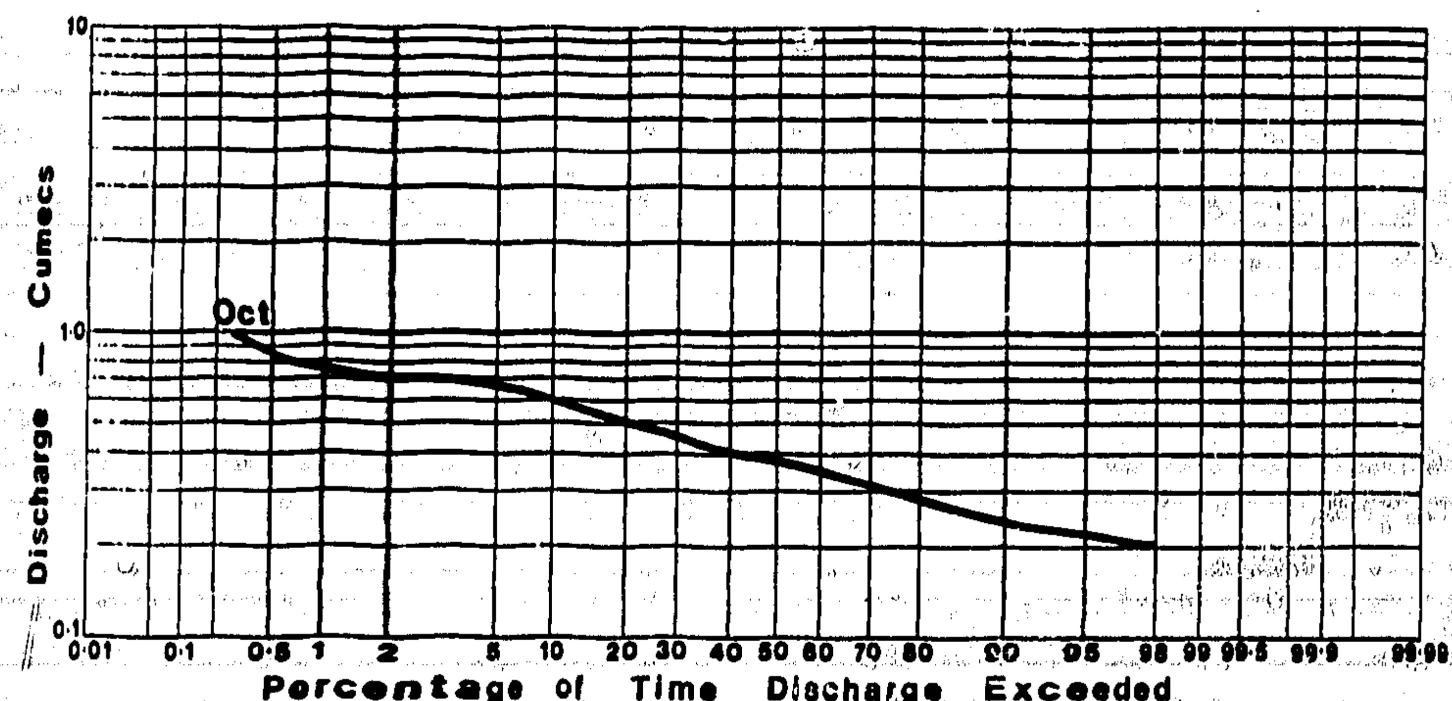

FIGURE 1.3 **OCTOBER MONTHLY FLOW DURATION CURVE FOR THE RIVER PANG**

1.3 VARIABILITY OF CALENDAR MONTH FLOW DURATION CURVES

There can be large differences in monthly flow duration curves between different months for the same catchment and also between different catchments for the same month. The position of the flow duration curve for any month is controlled primarily by the scale of the runoff process, that is large catchments in an area of high average annual rainfall will obviously have higher daily flows than small catchments in a low rainfall area. This pattern is also apparent when comparing monthly flow duration curves for the same catchment: the wetter winter months will generally have flow duration curves which plot above the drier summer months - this is illustrated in Figure 1.4. Thus the dominant variable controlling the position of any monthly flow duration curve is the average discharge in that month. A second order influence is the effect of geology on the flow regime which results in permeable catchments having flatter flow duration curves (i.e. small variation in mean daily flows) than impermeable catchments. These experience a wide range of daily flows and hence display steeper flow duration curves.

In this study it has thus been necessary to quantify both the location and the gradient of the monthly flow duration curves. Our analysis of over 500 catchments has indicated that the annual flow duration curve provides a good guide to the variability of monthly flow duration curves both in respect of the gradient and the position of the curves. Indeed, if the monthly curves are standardised by monthly runoff there is little variability between the twelve monthly curves through the year for a particular catchment. However, variations in the gradient of the curve between permeable and impermeable catchments do remain.

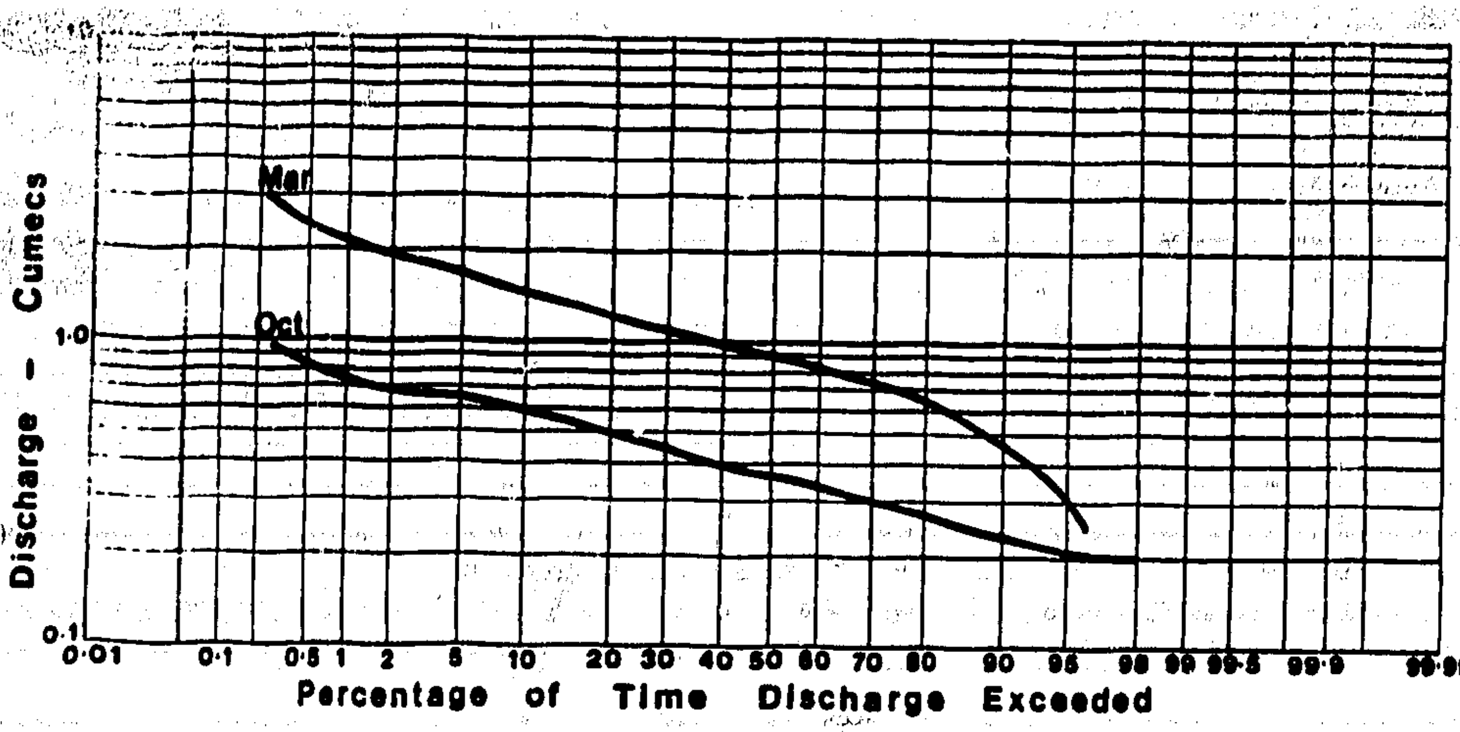

FIGURE 1.4 MARCH AND OCTOBER MONTHLY FLOW DURATION CURVES FOR THE PANG

1.4 SEASONAL FLOW DURATION CURVES

The previous sections have been concerned with the construction and explanation of individual calendar month flow duration curves; this section illustrates how two or more such monthly curves can be combined to form a seasonal flow duration curve. To avoid any confusion, all references to seasonal curves should be taken to mean flow duration curves covering two or more calendar months.

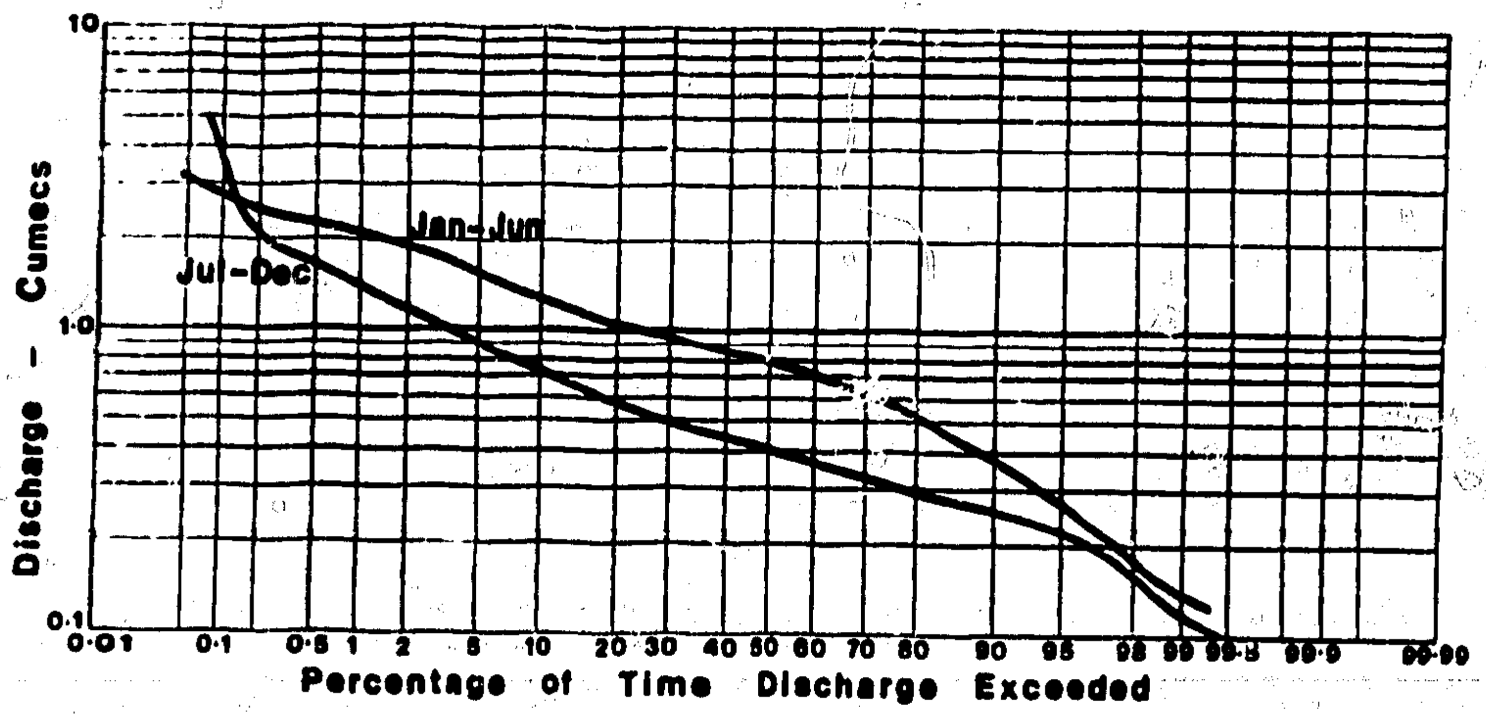

FIGURE 1.5 SIX MONTH SEASONAL FLOW DURATION CURVES FOR PANG

Figure 1.5 illustrates the differences between two six-month curves for the same catchment. As the Pang catchment is very permeable, the flows during the first six months of the year are in the main higher than for the rest of the year and this has resulted in the January-June curve being higher than that for July-December. It can be seen that the long term average flow of 0.65 cumecs is exceeded on 65% of days within the period January-June, but on only 15% of days during the rest of the year. The gradients of the two curves overall are similar indicating that whilst the daily flows over the period July-December are smaller in magnitude, they are just as variable.

The two curves on Figure 1.5 have been constructed for six month periods, but seasonal curves can be derived for between two and eleven month periods. An example in this manual calculates a seasonal curve covering the two month period July-August for the river Pang, both from data and using techniques recommended for the case where no data are available.

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1.5 COMPARISON OF CURVES IN DIMENSIONLESS FORM

At this point, some nomenclature is outlined. Throughout the report, the average discharge over any particular month or season will be designated AMD with the period following immediately in brackets. Thus the average discharge for July is written AMD(July) and is expressed in cumecs. Later in the report, mention is made of the long term annual runoff volume ARV, and the percentage which occurs in each of the twelve calendar months. This monthly runoff is designated MRV with the appropriate calendar month in brackets following. The monthly runoff volume for August is thus designated MRV(Aug) and is always expressed as a percentage of the annual runoff volume. Daily mean discharge data provide adequate accuracy for constructing monthly and seasonal flow duration curves.

Thus far, all figures illustrating monthly and seasonal flow duration curves have had their ordinates expressed in cumecs. This is entirely desirable for practical applications where a particular curve is used in isolation, but is unsatisfactory where two or more curves need to be compared. For example flow duration curves drawn for two catchments, one very much larger than the other, would be difficult to compare because of the differences in magnitude of the daily flow values originating from the two catchments. This problem can be resolved by dividing the ordinates of the curve by the mean discharge. In addition to assisting the comparison of curves this also enables comparisons to be made with those estimated from the methods given in section 3 of this report. Figure 1.6 repeats the information of Figure 1.4 with the discharge axis standardised by the monthly average flow, AMD.

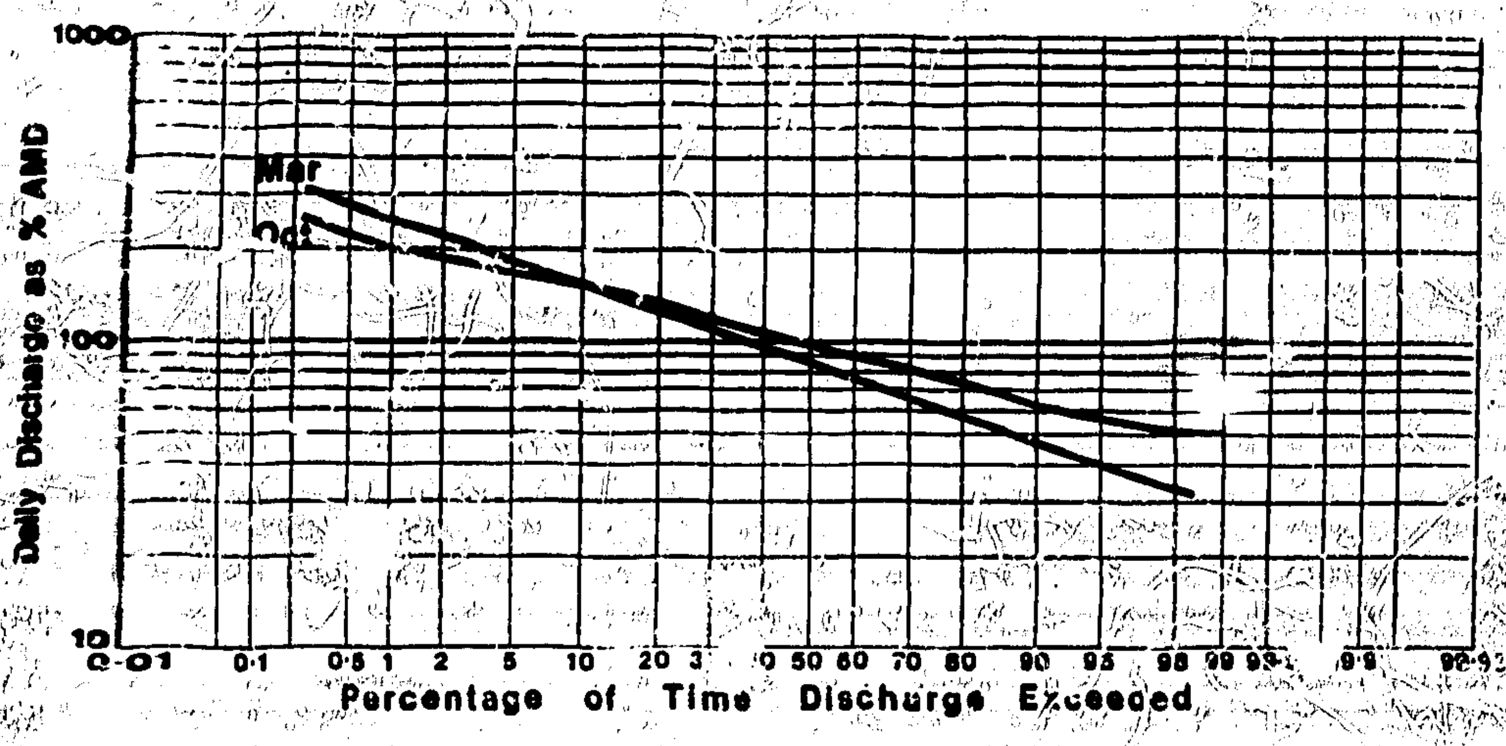

FIGURE 1.6 MARCH AND OCTOBER MONTHLY FLOW DURATION CURVES FOR THE PANG EXPRESSED AS PERCENTAGE OF AVERAGE MONTHLY DISCHARGE

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1.6 OUTLINE OF ESTIMATION PROCEDURE

The procedure for estimating the seasonal flow duration curve depends on the length of data available at the site of interest. Figure 1.7 outlines the three main approaches and the sections where they are to be found, although an individual problem may well make use of elements from all three sections.

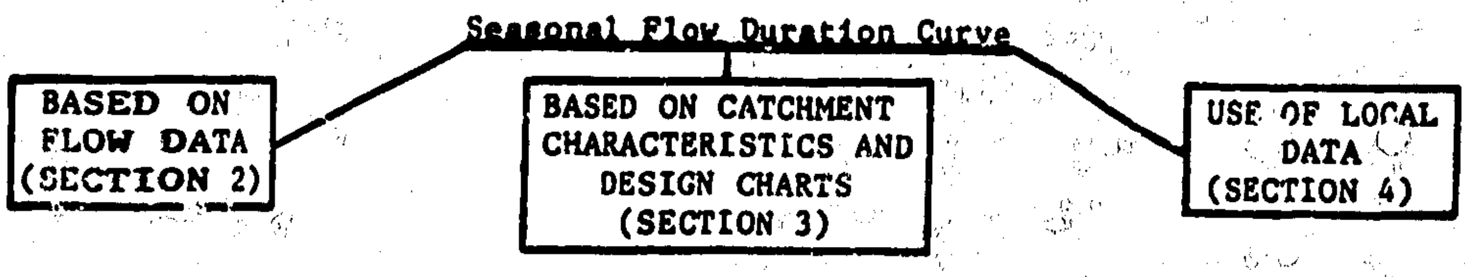


FIGURE 1.7 OUTLINE OF ESTIMATION PROCEDURE

Which of the three procedures to use depends on the amount of data available at the site of interest.

More than ten years	Use recommendations contained within section 2 in their entirety
Two to ten years	Use the data available to calculate a value of Q95(10) directly and then follow section 3.
Less than two years	Use section 3 recommendations in their entirety, although section 4.1 should be referred to if some data is available.

These are guidelines but there will be instances where departing from them is justified. If there were eight or nine years of data it could be useful to use both sections 2 and 3 and then to compare the two curves.

2.1 CONSTRUCTION OF MONTHLY FLOW DURATION CURVE ON LOG-NORMAL GRAPH PAPER

Table 2.1a shows the number of days which fall within each class interval for the three practice catchments. For the practice catchment selected, complete the table in a similar manner to that shown on Table 2.1, then plot the lower bound of each class interval against the corresponding entry in the final column on Figure 2.1a.

FALLOCH 11 YEARS (JAN)		LANGDON 11 YEARS (JAN)		ROMAN 14 YEARS (JAN)		NUMBER > BOTTOM OF c.i.	% GREATER THAN BOTTOM OF c.i.
c.i.	TOTAL IN INTERVAL	c.i.	TOTAL IN INTERVAL	c.i.	TOTAL IN INTERVAL		
0–1	49	0–0.1	48	0–0.1	28		
1–2	56	0.1–0.2	72	0.1–0.2	162		
2–3	34	0.2–0.3	49	0.2–0.3	86		
3–4	20	0.3–0.4	31	0.3–0.4	56		
4–5	17	0.4–0.5	21	0.4–0.5	31		
5–6	10	0.5–0.6	12	0.5–0.6	12		
6–7	11	0.6–0.7	10	0.6–0.7	14		
7–8	17	0.7–0.8	9	0.7–0.8	10		
8–9	4	0.8–0.9	8	0.8–0.9	7		
9–10	12	0.9–1.0	7	0.9–1.0	6		
10–11	11	1.0–1.1	7	1.0–1.1	1		
11–12	9	1.1–1.2	4	1.1–1.2	3		
12–13	2	1.2–1.3	8	1.2–1.3	2		
13–14	5	1.3–1.4	7	1.3–1.4	4		
14–15	6	1.4–1.5	3	1.4–1.5	3		
15–16	8	1.5–1.6	4	1.5–1.6	1		
16–17	6	1.6–1.7	4	1.6–1.7	-		
17–18	4	1.7–1.8	5	1.7–1.8	-		
18–19	8	1.8–1.9	3	1.8–1.9	1		
19–20	6	1.9–2.0	4	1.9–2.0	-		
20+	46	2.0+	25	2.0+	7		
	Σ = 341		Σ = 341		Σ = 434		

TABLE 2.1a PREPARATION OF JANUARY FLOW DURATION CURVE DATA FOR

2. THE GAUGED CATCHMENT CASE

2.1 CONSTRUCTION OF MONTHLY FLOW DURATION CURVE ON LOG-NORMAL GRAPH PAPER

The particular example illustrated in this section shows the construction of a January monthly flow duration curve from data: however, the procedure is identical for any month.

The daily average flow data are sorted into conveniently chosen, equal and constant width class intervals (ci) expressed in discharge units. For the River Pang the discharges experienced during the month of January over the 16 year period between 1969 and 1984 range between 0.2 and 2.4 cumecs. The class interval width is chosen to give the degree of definition required; in the example case a figure of 0.1 cumecs is appropriate. Each day's discharge is assigned to its appropriate class interval (in Table 2.1) and a count made of the number of days within each interval. The number of days above the lower limit of each ci is entered in column 3 which is then expressed as a percentage exceedance in column 4 by dividing the entry in column 3 by 496, the total number of days in the record, and multiplying by 100.

The exercise has been completed for the river Pang, the results being entered into Figure 2.1.

(1) Class interval cumecs	(2) Total in class interval	(3) Number greater than bottom of ci	(4) Percentage greater than bottom of ci
2.4–2.5	0	0	0.0
2.3–2.4	1	1	0.2
2.2–2.3	3	4	0.8
2.1–2.2	3	7	1.4
2.0–2.1	3	10	2.0
1.9–2.0	8	18	3.6
1.8–1.9	3	21	4.2
1.7–1.8	5	26	5.2
1.6–1.7	6	32	6.5
1.5–1.6	14	46	9.3
1.4–1.5	8	54	10.9
1.3–1.4	11	65	13.1
1.2–1.3	14	79	15.9
1.1–1.2	22	101	20.4
1.0–1.1	19	120	24.2
0.9–1.0	40	160	32.3
0.8–0.9	51	211	42.5
0.7–0.8	38	249	50.2
0.6–0.7	74	323	65.1
0.5–0.6	74	397	80.0
0.4–0.5	59	456	91.9
0.3–0.4	15	471	95.0
0.2–0.3	25	496	100.0
	Σ = 496		

TABLE 2.1 PREPARATION OF JANUARY FLOW DURATION CURVE DATA FOR PANG CATCHMENT

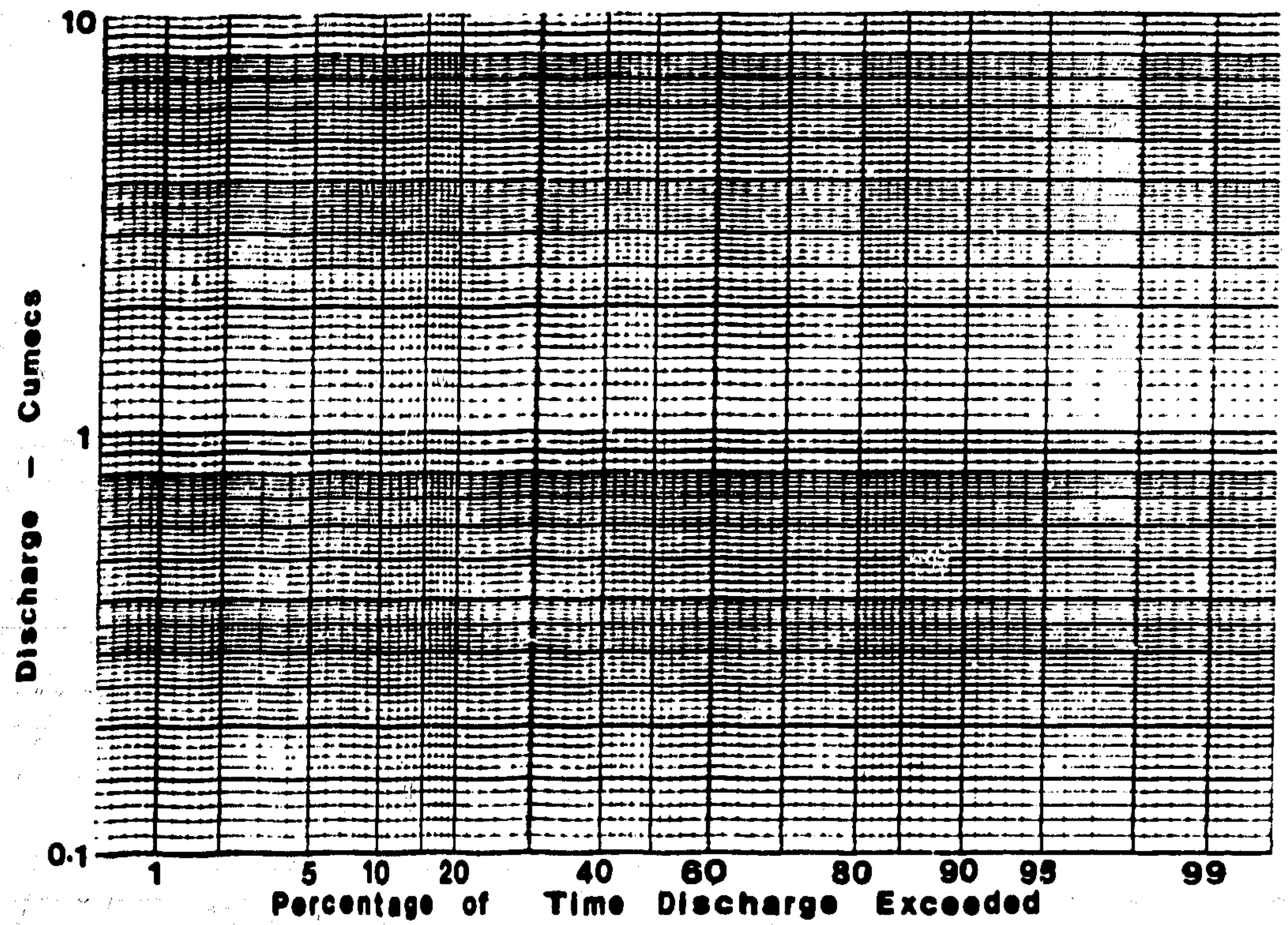


FIGURE 2.1a JANUARY MONTHLY FLOW DURATION CURVE FOR PRACTICE CATCHMENT

Figure 2.1 shows graphically the contents of Table 2.1. Each point on the figure is derived from the use of one row from Table 2.1. The lower bound of each class interval is used to fix the position on the ordinate, the corresponding point on the abscissa coming from column 4. For example, the class interval 1.0-1.1 cumecs has 120 of the total of 496 flow values greater than 1.0 cumec. Thus (120/496) x 100 or 24.2% of the time, the flow level 1.0 cumec is exceeded.

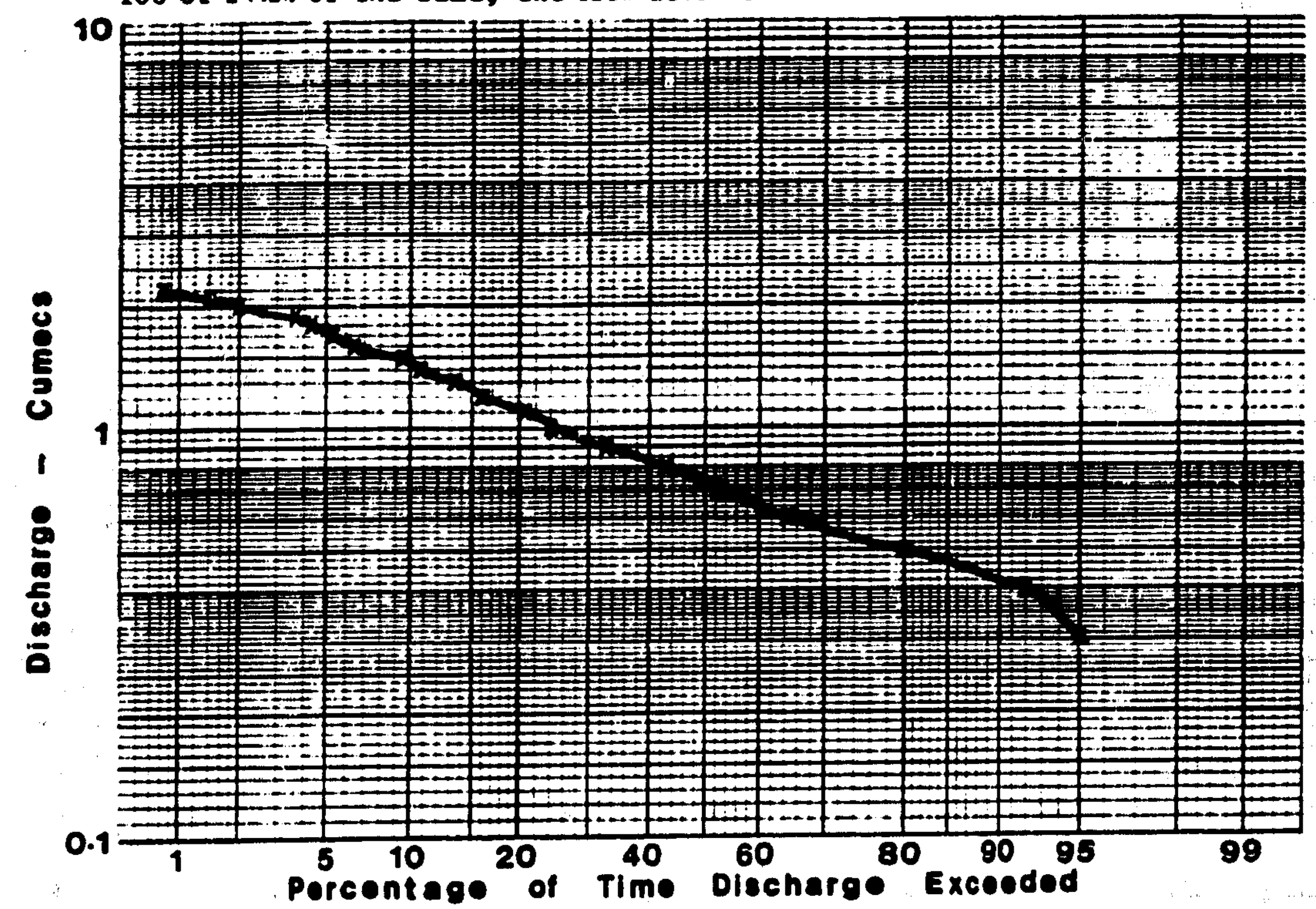


FIGURE 2.1 JANUARY MONTHLY FLOW DURATION CURVE FOR PANG CATCHMENT

Log-normal paper has been used to construct Figure 2.1. However, if none is available, linear graph paper can be used in conjunction with a technique for assigning a standard Normal deviate to the abscissa corresponding to the column 4 probabilities. In place of the daily flow values being plotted on a logarithmic ordinate, the logs of the daily flows can be plotted on a linear ordinate. The method itself is presented in detail in section 2.3 of Report 2.1. The result is identical to that produced by the method outlined in this report.

2.2 CONSTRUCTION OF SEASONAL FLOW DURATION CURVE ON LOG-NORMAL GRAPH PAPER

The technique for constructing a seasonal curve is practically identical to that for constructing a monthly curve. The only difference is that the daily flow data are taken from as many different calendar months as are required to make up the seasonal curve. Clearly seasonal curves will contain more daily flow values than a monthly curve constructed from the same flow record.

3.1 INTRODUCTION AND OUTLINE

Details of the three practice catchments can be found in Report 2.1, Chapter 1, Basic Data. Select the same catchment as was used in the gauged catchment case and complete the corresponding calculations as are executed for the River Pang.

3. THE UNGAUGED CATCHMENT CASE

3.1 INTRODUCTION AND OUTLINE

This section describes a procedure for estimating monthly and seasonal flow duration curves at sites where little or no flow data are available. The method is founded on estimating the 95 percentile, 10 day flow from the annual flow duration curve, Q95(10). The estimate of Q95(10) requires a knowledge of the catchment's annual average rainfall (SAAR) and baseflow index (BFI). The full method for estimating Q95(10) will be found in Report 2.1 and salient points for the ungauged case are repeated here in section 3.2.

Before embarking on the practice exercise it may be helpful to review the procedure in its totality. The following summary list of steps should assist in placing each step in the context of the entire calculation.

(1) Estimate Q95(10) from catchment characteristics. At this point the result is expressed as a percentage of the average discharge of the catchment (section 3.2).

(2) Enter Figures 3.2a and 3.2c with the previous result to determine Q95 and Q5 for the particular months of interest. At this point the results are expressed in terms of the average flow of those months (section 3.3).

(3) Using the suggested procedure of section 3.4 to derive the average flow, convert this to monthly runoff volume (MRV) with figures 3.6 and 3.7, or tables 3.2 and 3.2a.

(4) Rescale the results of step (2) to cumecs using the appropriate value from step (3).

(5) If seasonal flow duration curves are required, covering a period of two or more months, it will be necessary to combine the appropriate monthly curves. Instructions on how this is achieved are described in section 3.5.

The remaining steps in the procedure for estimating monthly and seasonal flow duration curves require no further use to be made of catchment characteristics, but depend on a set of tables and diagrams. The first of these diagrams, Figures 3.2 (a & c), allow the standardised Q95 and Q5 values to be obtained for any month which in turn, are rescaled to discharge terms using information on the mean monthly flow distribution contained in Figures 3.6 and 3.7, and Tables 3.2 and 3.2a. The relations apply to rivers of all types and in all parts of the United Kingdom.

3.2 ESTIMATION OF 95 PERCENTILE 10 DAY FLOW

The example catchment is in hydrometric area ------ and therefore in region ----. Substituting the catchment characteristic values into the appropriate equation.

$$\sqrt{Q95(10)} = \text{---}\sqrt{BFI} + \text{-----}\sqrt{\quad} - \text{----}$$

$$=$$

$$\therefore \; Q95(10) = \text{-----} \; \%\, ADF$$

Values of BFI, SAAR, and L would at an ungauged site be normally estimated from maps. However, in the case of the three practice catchments, these values are known and can be used instead of resorting to maps if desired.

	BFI	SAAR	L
Falloch	0.18	3020	-
Langdon	0.20	1621	-
Roman	0.62	581	15.35

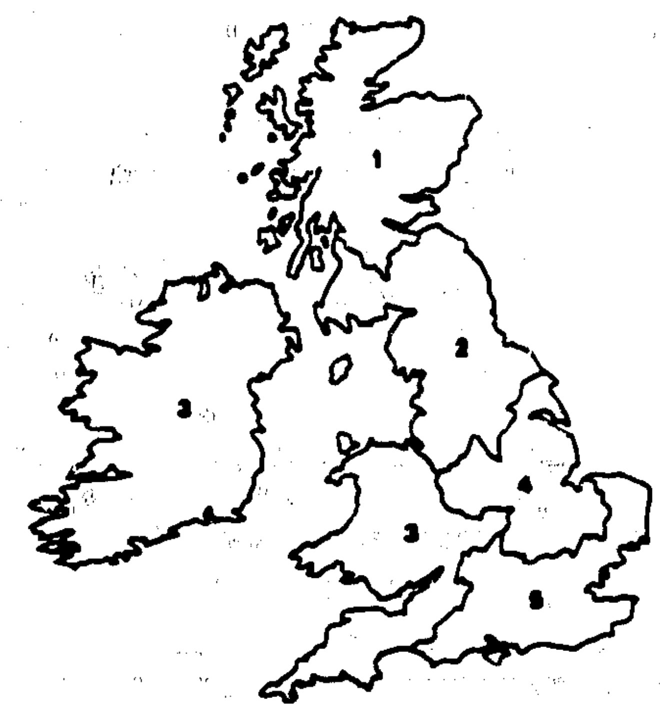
3.2 ESTIMATION OF 95 PERCENTILE 10 DAY FLOW

Table 3.1 shows the regression equations to use in the regions of the country shown in Figure 3.1. The equations give an estimate of the 95 percentile from the 10 day flow duration curve, Q95(10) in units of %ADF.

SAAR is the 1941-1970 standard average rainfall in mm and BFI is the catchment's baseflow index which is estimated at the ungauged site from catchment geology. Report No. 3, section 3.2 shows the procedure.

TABLE 3.1. Regional external relationship regression equations

Eqn No	Hydrometric areas	Equation $\sqrt{Q95(10)}$ =
1	1-19, 84-97, 104-108	$7.60\sqrt{BFI}+0.0263\sqrt{SAAR}-1.46$
2	20-25, 27, 68-83, 103	$7.60\sqrt{BFI}+0.0263\sqrt{SAAR}-1.84$
3	45-67, 102, 201-223	$7.60\sqrt{BFI}+0.0263\sqrt{SAAR}-2.16$
4	26, 28-33	$11.9\sqrt{BFI}+0.1150\sqrt{SAAR}-8.03$
5	34-44, 101	$8.51\sqrt{BFI}+0.0211\sqrt{L}-1.91$



Eqn. Hydrometric Areas.
1 1-19,84-97,104-108
2 20-25,27,68-83,103
3 45-67,102,201-223
4 26,28-33
5 34-44,101

FIGURE 3.1 KEY MAP TO EXTERNAL REGIONAL RELATIONSHIP

Using equation 5 (the Pang catchment is in hydrometric area 39) and the value of BFI=0·9 and L=26·9 km

$$\sqrt{Q95(10)}=8.51\sqrt{0{\cdot}9}+0.0211\sqrt{26{\cdot}9}-1.91$$

$$=6{\cdot}273$$

so $Q95(10)=39{\cdot}35$ %ADF

3.3 ESTIMATION OF FLOW DURATION CURVE AS PERCENTAGE OF AVERAGE MONTHLY DISCHARGE

Use Figures 3.2(a & c) in association with the value of Q95(10) derived for the practice catchment in section 3.2, to interpolate values for Q95 and Q5. This exercise must be done for each month to be incorporated in the seasonal curve, in this instance July and August.
Use Figures 3.3(a & c) to plot the values of Q95 and Q5 for both July and August, and hence draw the respective monthly flow duration curves.

	July	*August*
Q95 =		
Q5 =		

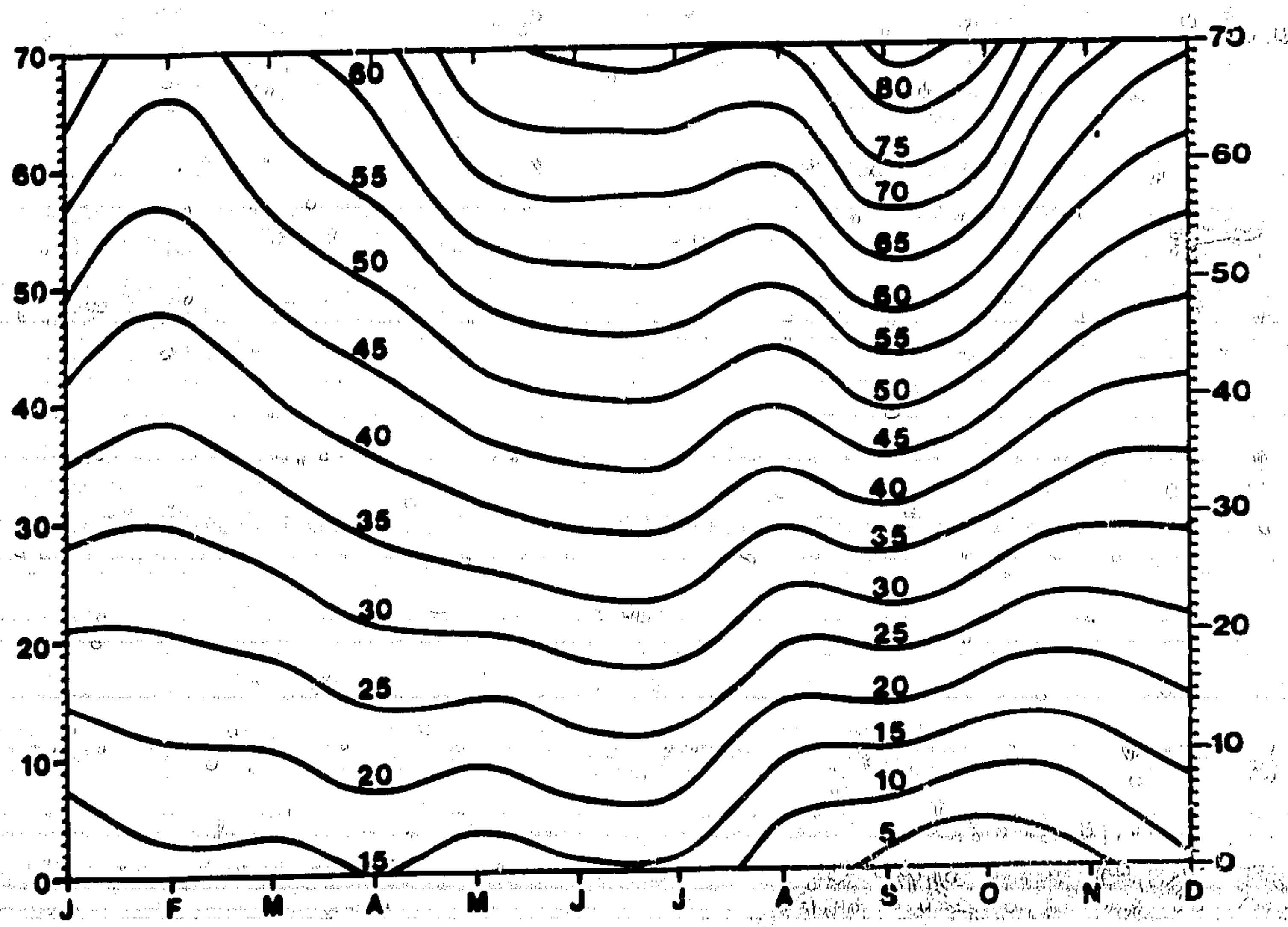


FIGURE 3.2a PREDICTION OF Q95 FOR EACH MONTH

3.3 ESTIMATION OF FLOW DURATION CURVE AS PERCENTAGE OF AVERAGE MONTHLY DISCHARGE

Estimates of Q5 and Q95 are needed for both July and August. Two figures are illustrated which allow the direct estimation of these two percentiles for each month. The value of Q95(10), 39.35% ADF, is used to enter the Figures on their respective ordinates, and to scale across each figure to read off the appropriate percentile for both months, on each figure. It will be found necessary to interpolate between contour lines to arrive at accurate estimates. The 95 and 5 percentiles for both July and August have been marked on Figures 3.2b and 3.2d

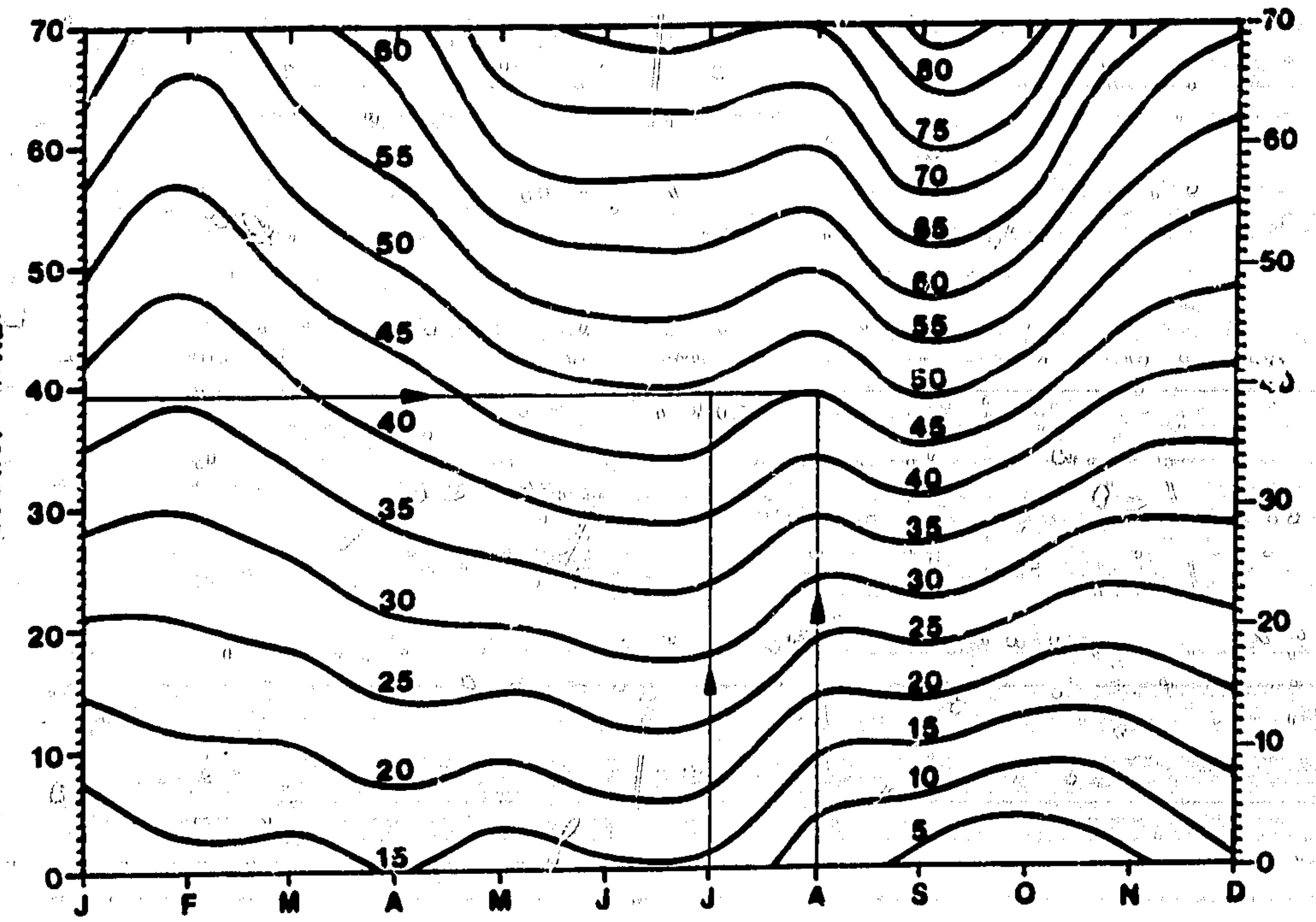


FIGURE 3.2b INTERPOLATING Q95 FOR JULY AND AUGUST

	July	August
Q95 =	49	45
Q5 =	155	175

It is emphasised that these results are expressed in terms of their respective month's AMD. For example, July's Q95 is 49% of the July AMD.

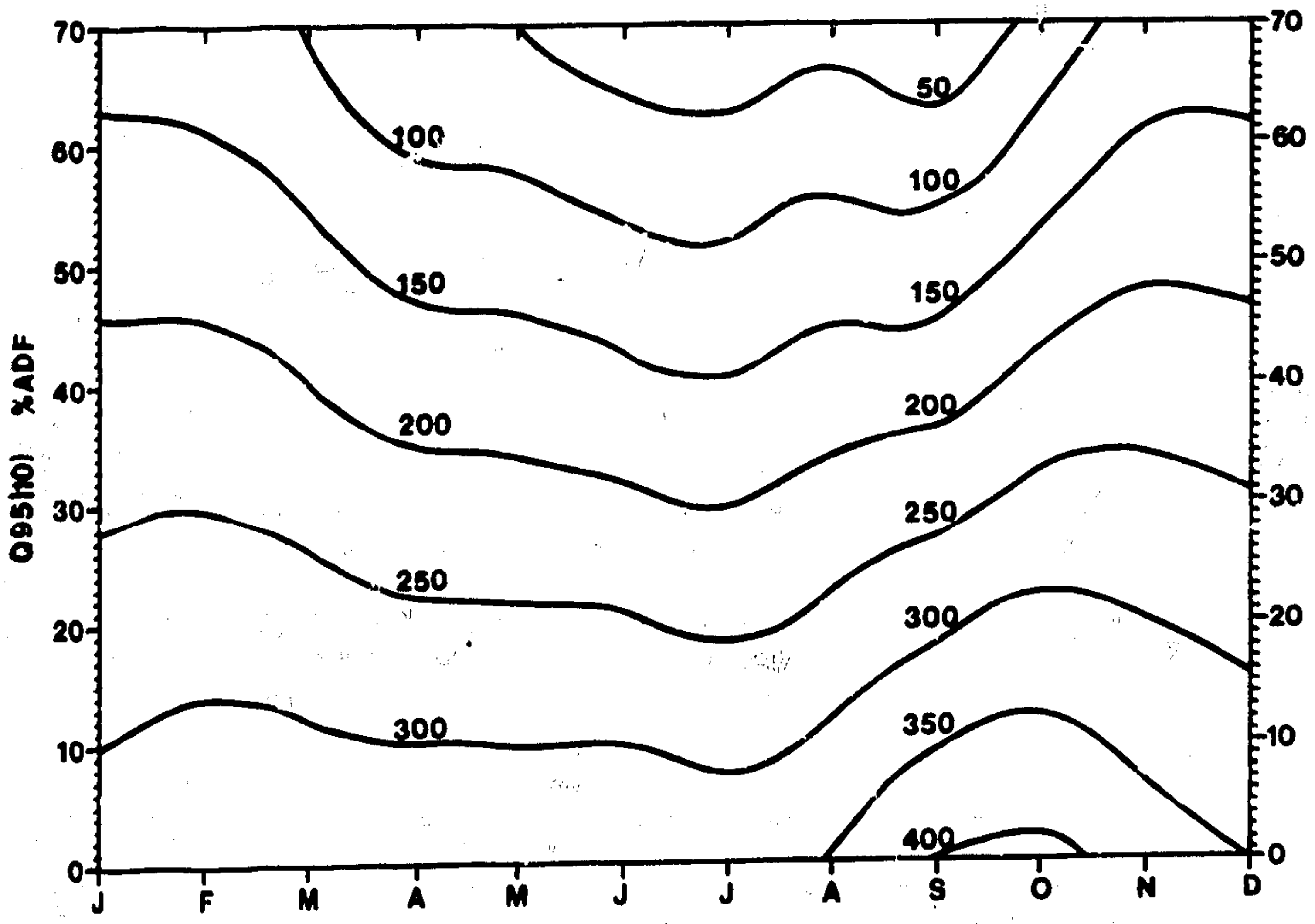


FIGURE 3.2c PREDICTION OF Q5 FOR EACH MONTH

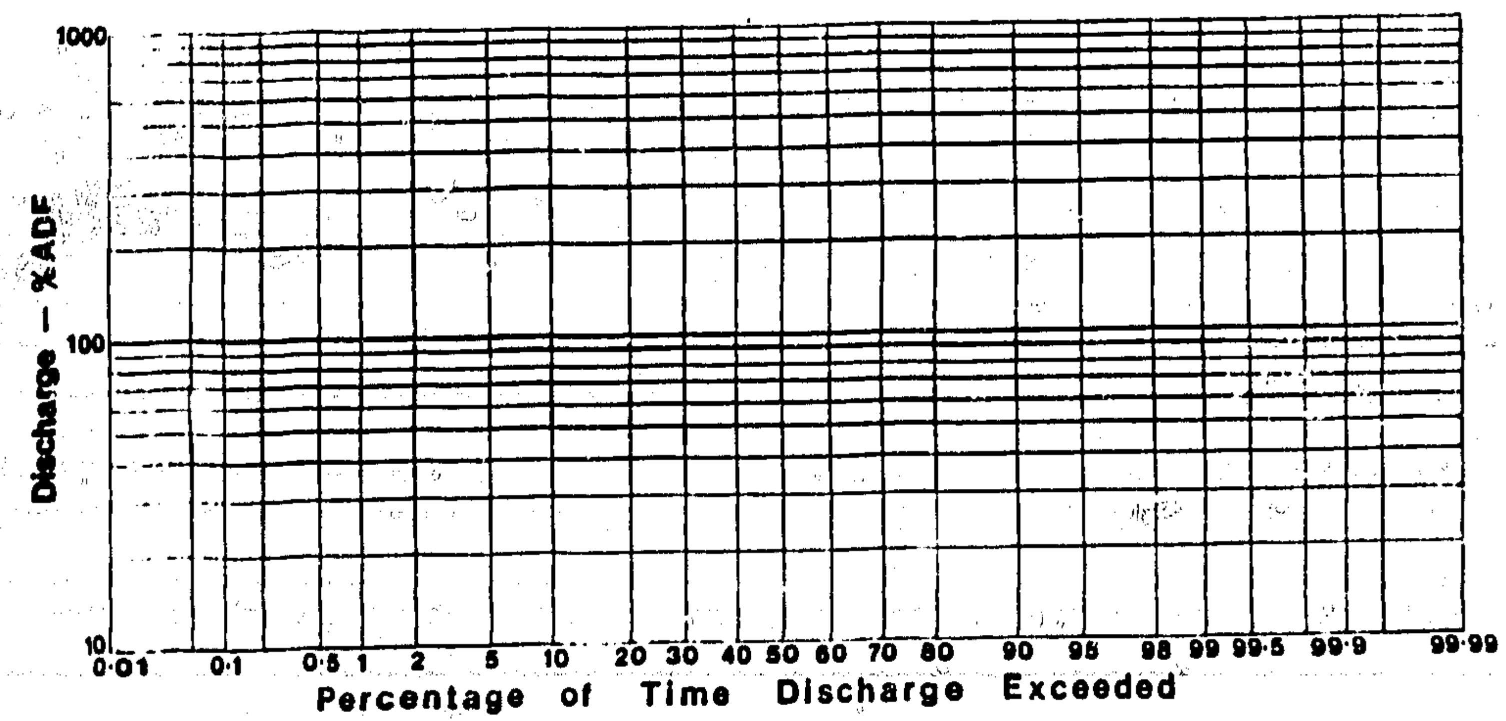


FIGURE 3.3a MONTHLY FLOW DURATION CURVES AS %ADF FOR PRACTICE CATCHMENT

A flow duration curve should be linearly interpolated and extrapolated using the 5 and 95 percentiles for each month required. Figure 3.3 is provided for this purpose. The next section describes how to rescale the ordinates to cumecs.

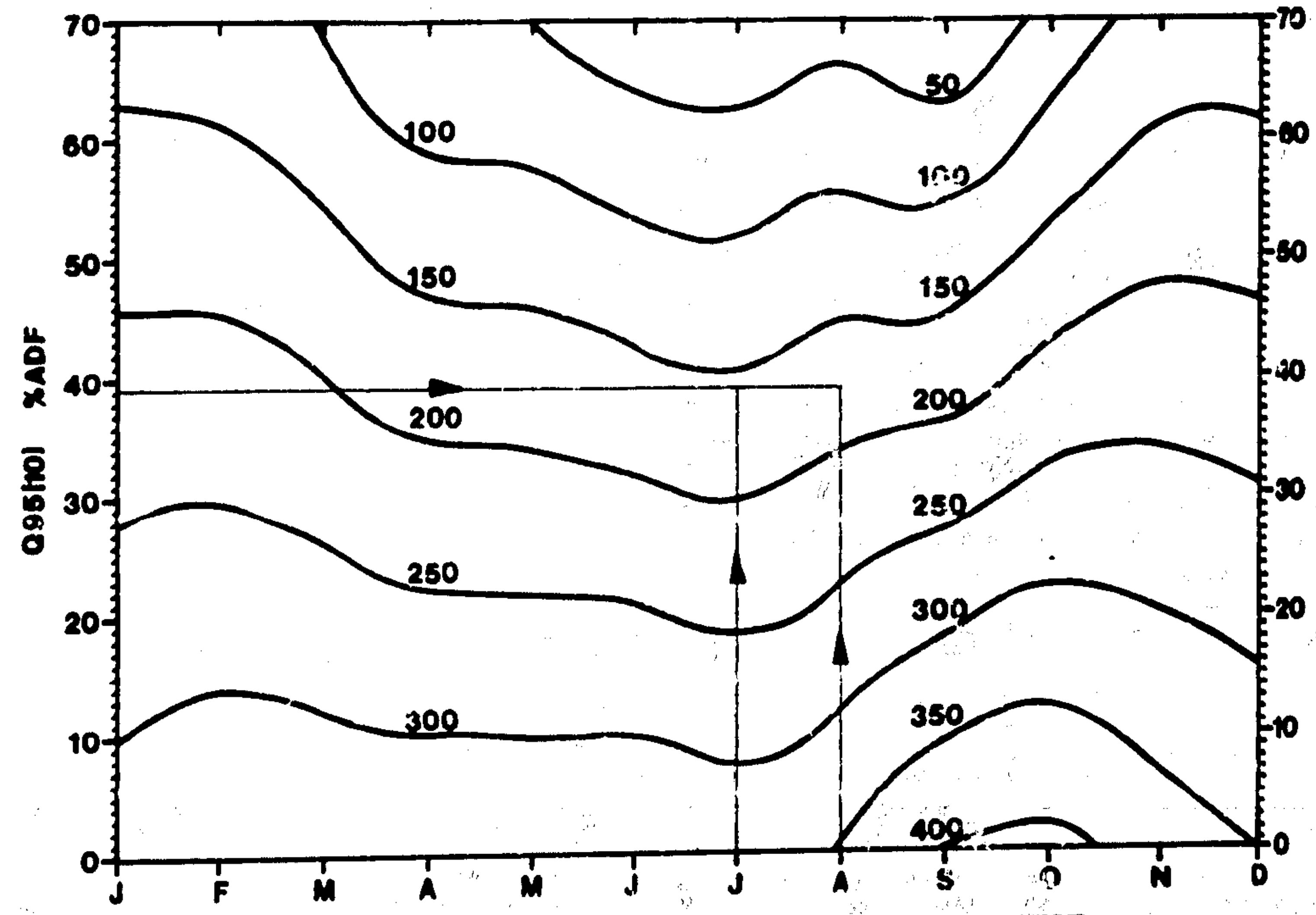


FIGURE 3.2d INTERPOLATING Q5 FOR JULY AND AUGUST

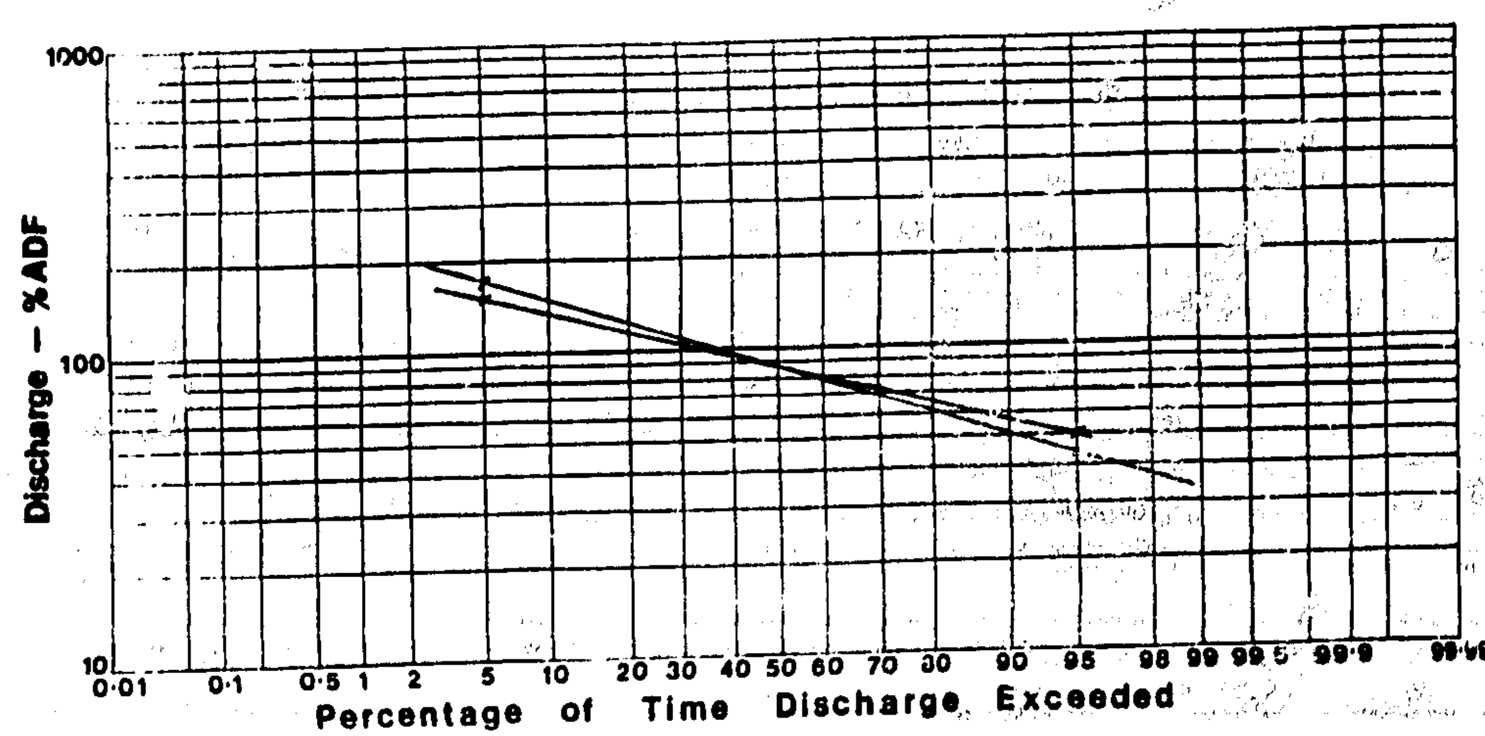


FIGURE 3.3 MONTHLY FLOW DURATION CURVES AS %ADF FOR JULY AND AUGUST FOR PANG

3.4 CALCULATION OF AVERAGE DISCHARGE (ADF)

The values of SAAR and PE can be abstracted from maps as detailed overleaf; however the values required are also listed for reference.

	SAAR(mm)	PE(mm)	AREA(km^2)
Falloch	2700	375	80.3
Langdon	1600	400	13.0
Roman	570	542	52.6

For the .... catchment, SAAR = ..., and

therefore the reduction ratio r is ....

AE = r x PE = ... x .... = ...

Annual runoff; ADF = SAAR − AE = ... − .... = ... mm

= 0.00003171 x AREA x Annual runoff mm

= 0.00003171 x .... x .... = ... cumecs

3.4 CALCULATION OF AVERAGE DISCHARGE (ADF)

Report 3 of the Low Flow Series, P9, contains recommendations for estimating the long term average flow, using mapped values of potential evaporation (PE), or long period data at a nearby site. Potential evaporation is estimated from the Meteorological Office 1:2,000,000 map of annual average potential evaporation.

PE = 540 mm

This figure is then reduced to actual evapotranspiration (AE) using the tabulated factor r and AE = r x PE.

SAAR	500	600	700	800	900	1000	1100
r	0.88	0.90	0.92	0.94	0.96	0.98	1.00

For the Pang catchment AE = 0.92 x 540 = 497 mm

Annual runoff = SAAR − AE = 722 − 497 = 225 mm

Convert mm to cumecs by multiplying the mm figure by 0.00003171 x AREA = 0.00542

ADF = 0.00542 x 225 = 1.22 cumecs.

3.5 ESTIMATION OF MONTHLY RUNOFF VOLUME (MRV)

None of the three practice catchments are in Northern Ireland, therefore use the value of Q95(10) estimated in section 3.1 to decide whether paragrpahs (b) or (c) opposite, are appropriate. Then use the appropriate figure or table to determine MRV for each month required.

Northern Ireland	*Use*
All catchments	*Table 3.2*
Great Britain	
0<Q95(10)<15	*Figure 3.6*
15<Q95(10)<30	*Figure 3.7*
30<Q95(10)	*Table 3.2a*

3.5 ESTIMATION OF MONTHLY RUNOFF VOLUME (MRV)

In this section, the procedure for estimating monthly runoff volume (MRV) at an ungauged site in the UK is presented. Remember that MRV is expressed as a percentage of long term annual runoff volume. All catchments fall within one of three categories leading to a different method of MRV estimation in each case.

(a) Catchments in Northern Ireland

(b) Catchments in Great Britain with Q95(10) < 30%

(c) Catchments in Great Britain with Q95(10) > 30%

(a) Table 3.2 gives MRV values for each month for all Northern Ireland catchments. The values shown are average ones for use throughout Northern Ireland and have been compiled from an anlaysis of 21 gauging records distributed across the country.

Table 3.2 **Monthly runoff volume (MRV) as percent for Northern Ireland catchments**

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
16.8	12.3	8.7	5.3	3.9	2.7	2.4	3.4	5.9	9.9	12.9	16.0

There is insufficient regional variation to justify any attempt at a higher level of accuracy, as would be provided by a contour map of MRV for each month. Table 3.2 is used in an identical manner to Table 3.2a which is used to explain the Pang example at the end of this section.

(b) The more impermeable catchments within Great Britain, those with a Q95(10) of less than 30%, display a significant regional variation in MRV which is represented by two series of monthly maps as follows.

0 < Q95(10) < 15	Figure 3.6 (1-12)
15 < Q95(10) < 30	Figure 3.7 (1-12)

(c) Table 3.2a gives MRV values for each month for those catchments in Great Britain which have a Q95(10) value greater than 30%. Most of such catchments are to be found on the chalk aquifers in central southern England and East Anglia.

Table 3.2a **Monthly runoff volume (MRV) as percent for G.B. catchments with Q95(10) > 30%**

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
11.8	14.2	13.0	10.3	8.1	6.4	5.0	4.6	4.5	5.3	7.0	9.8

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July MRV = - - - - - - - - - - - -

Aug MRV = - - - - - - - - - - - -

AMD(JULY) = $\dfrac{\text{-----} \times \text{-----}}{(100/12)}$ *cumecs*

AMD(AUG) = $\dfrac{\text{-----} \times \text{-----}}{(100/12)}$ *cumecs*

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For the Pang Q95(10) = 39.35 %ADF and so Table 3.2a rather than either of Figures 3.6 or 3.7 must be used. The following equation should be used to derive average monthly discharge from MRV, irrespective of whether MRV originates from Table 3.2, Table 3.2a, Figure 3.6, or Figure 3.7.

$$AMD = \frac{MRV \times ADF}{(100/12)}$$

The denominator arises from the fact that monthly and annual average discharge are calculated over different time periods and from the fact that MRV is expressed as a percent.

So for July: $AMD = \dfrac{5.0 \times ADF}{(100/12)} = 0.732$ cumecs

Similarly for August: $AMD = \dfrac{4.6 \times ADF}{(100/12)} = 0.673$ cumecs

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3.6 CONVERSION OF MONTHLY FLOW DURATION CURVE TO ABSOLUTE UNITS

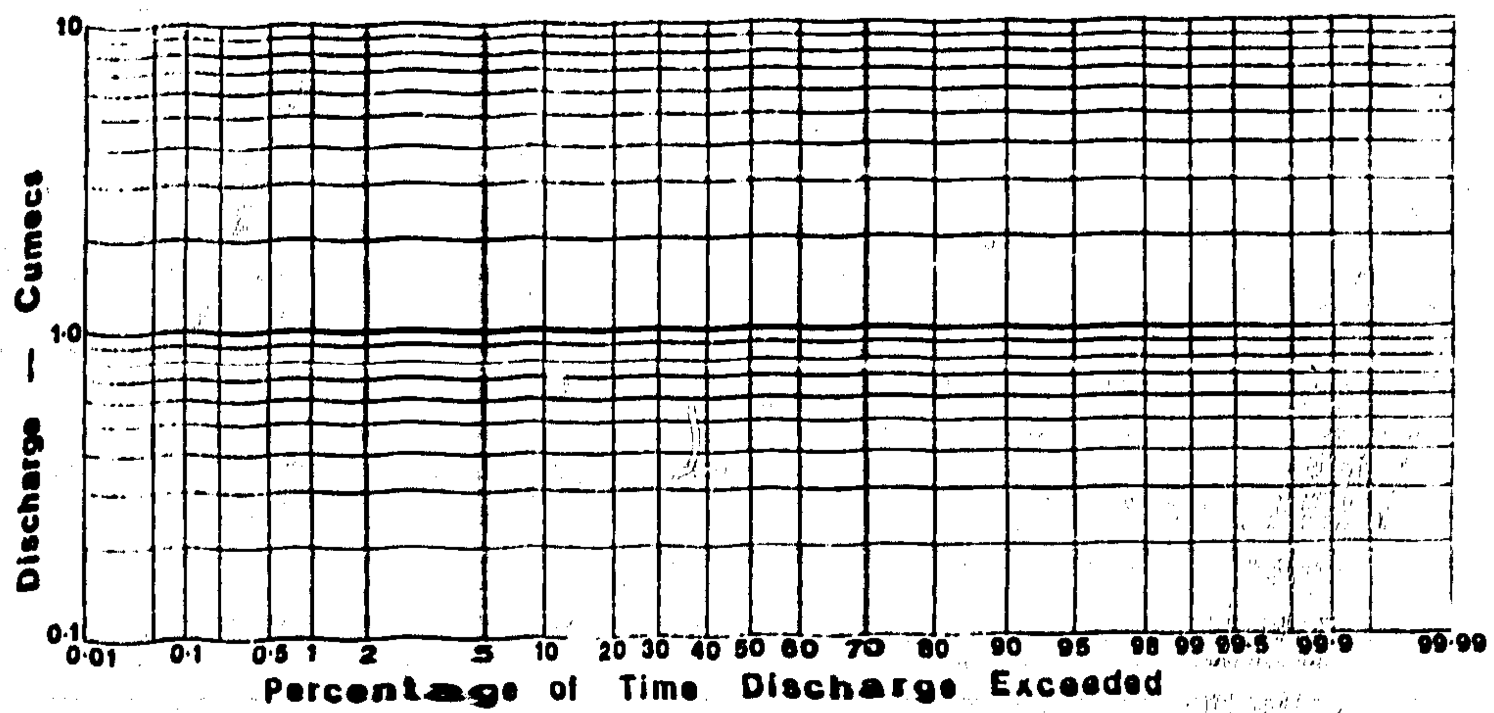

FIGURE 3.4a MONTHLY FLOW DURATION CURVES IN CUMECS FOR PRACTICE CATCHMENT

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3.6 CONVERSION OF MONTHLY FLOW DURATION CURVE TO ABSOLUTE UNITS

Previously calculated values of Q95 and Q5 originally expressed as a percent of their own AMD can now be rescaled to cumec terms and then plotted on Figure 3.4. If all that is required is a one calendar month flow duration curve e.g. for July alone, then the procedure terminates here. If however a seasonal curve composed of two or more calendar months is required, the next section contains details of how curves can be combined.

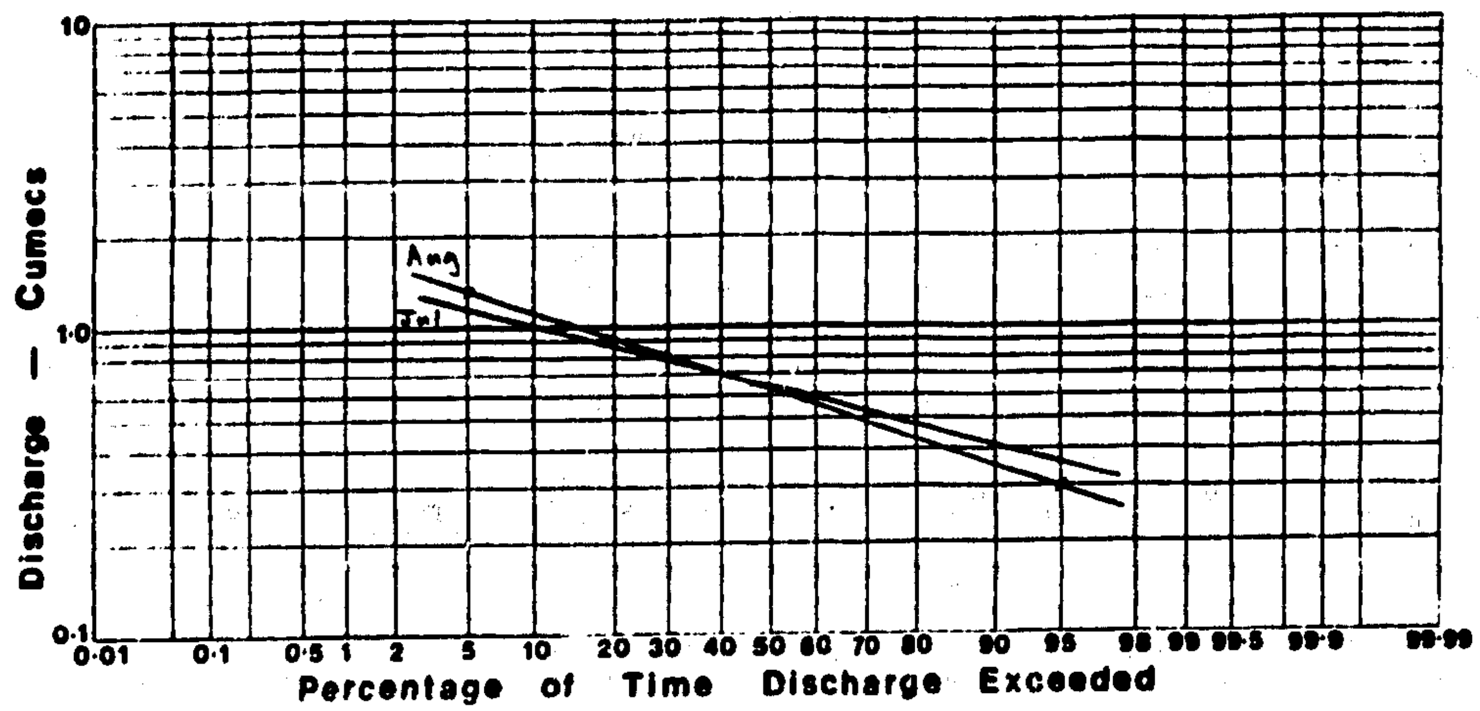

FIGURE 3.4 MONTHLY FLOW DURATION CURVES IN CUMECS FOR JULY AND AUGUST FOR PANG

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3.7 CONSTRUCTING SEASONAL FLOW DURATION CURVES FROM TWO OR MORE MONTHLY CURVES

Complete Table 3.3a below using information taken from Figure 3.4a. Choose discharges for which percentiles can be used from all monthly curves to be incorporated within the seasonal curve.

FLOW CUMECS	J	F	M	A	M	J	J	A	S	O	N	D	SEASONAL PERCENTILE

TABLE 3.3a MONTHLY PERCENTILES TO BE AVERAGED FOR PRACTICE CATCHMENT

3.7 CONSTRUCTING SEASONAL FLOW DURATION CURVES FROM TWO OR MORE MONTHLY CURVES

The example below shows the derivation of a flow duration curve for a season composed of July and August. The procedure is similar if three or more months are to be used. Percentiles from the curves for July and August, expressed in cumecs on Figure 3.4, are entered into Table 3.3 below.

Flow cumecs	J	F	M	A	M	J	J	A	S	O	N	D	SEASONAL PERCENTILE
0.3							98	95					96.5
0.4							90	84					87
0.5							73	69					71
0.6							57	55					56
0.7							40	40					40
0.8							27	30					28.5
0.9							17	20					18.5
1.0							10	15					12.5
1.1							5	10					7.5

TABLE 3.3 MONTHLY PERCENTILES TO BE AVERAGED FOR PANG

Average the percentiles for each month of the required season across the table. The resulting average figures are entered into the final column. This column when completed, becomes the abscissa of the seasonal curve, whilst column 1 provides the corresponding ordinate information. Figure 3.5 has been drawn using the first and final columns of Table 3.3, and is the end result of the method.
Any seasonal curve of between two and eleven months can be constructed in this way. Do not be tempted to average monthly flow duration curves vertically. This will give incorrect results especially if the individual curves are far separated. Also it is invalid to average standardised curves at the Figure 1.3 stage. The method presented above is the only correct approach.

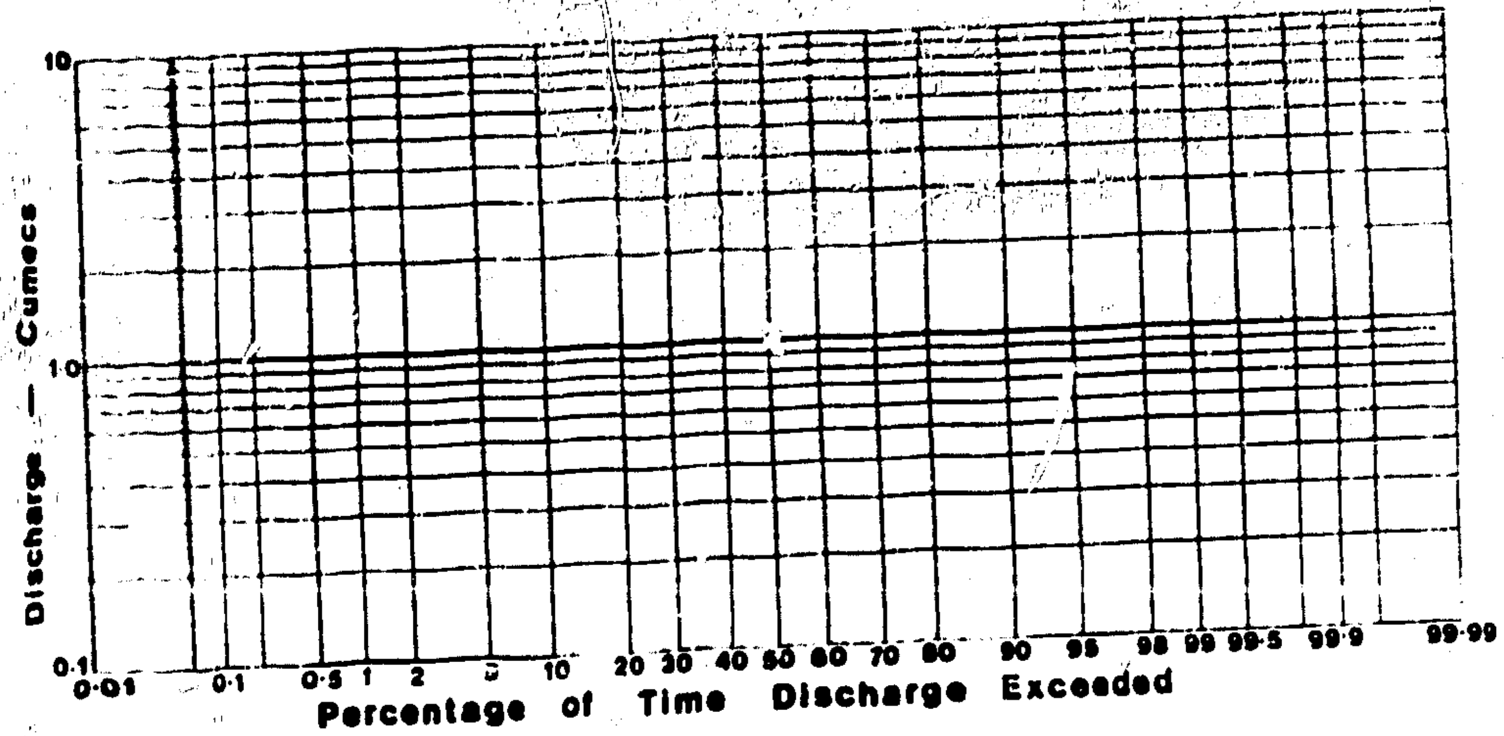

FIGURE 3.5a SEASONAL FLOW DURATION CURVE IN CUMECS FOR PRACTICE CATCHMENT

Note that seasonal flow duration curves constructed from two or more calendar months need no longer plot as a straight line on the lognormal graph paper. It is suggested that an eye guided straight line is drawn through the plotted points.

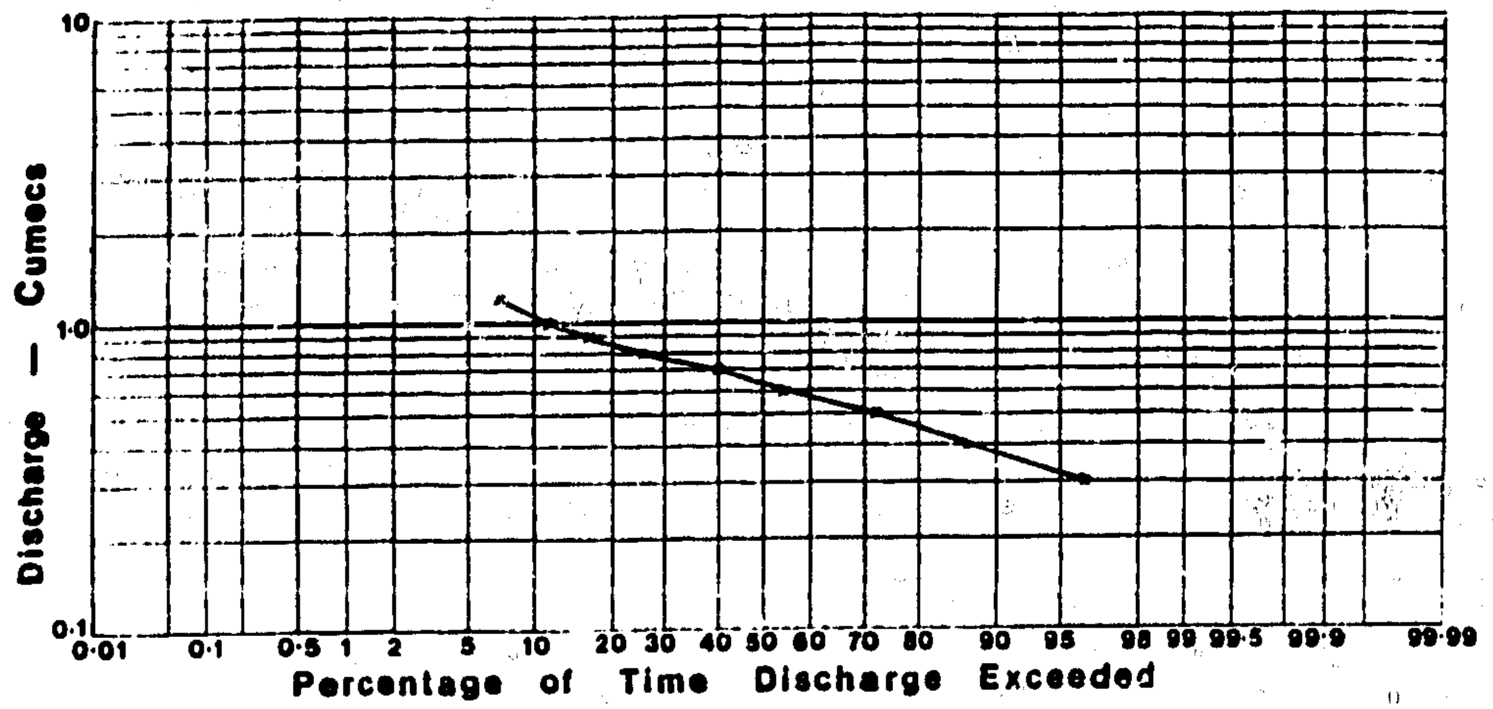

FIGURE 3.5 SEASONAL FLOW DURATION CURVE IN CUMECS FOR JULY AND AUGUST FOR PANG

4. USE OF LOCAL DATA

In this chapter a number of methods of incorporating short data records from or near the site of interest are outlined.

4.1 Data from the site of interest

If a temporary gauging structure has been installed at a site where a seasonal flow duration curve is needed, it is possible to make use of the short data period resulting

(a) If 1 or 2 years of data are available, use the ungauged technique outlined in Chapter 3 and make use of the data to calculate a BFI value by the method given in Report No.3, section 3.1. The BFI can then be used in the regression equation to allow a more accurate estimate of Q95(10) than would result by using a value of BFI arrived at by consideration of geological maps.

(b) If between 2 and 10 years data are available, use them to calculate a value of Q95(10) directly, Report 2.1, section 2.1, and continue with the ungauged recommendations in section 3.3 of this report. In addition use the data to calculate the percentage of the annual runoff occurring in each of the twelve months as a check on the value given by Figures 3.6, 3.7 or Table 3.2.

(c) If more than 10 years data are available, use the techniques of Chapter 2.

4.2 Data from a nearby site

The monthly flow duration curves are controlled primarily by the MRV distribution around the year. If there is a nearby site with sufficient record (e.g. 10 years) then we recommend strongly that its data be used to provide an estimate of MRV for the site and months of interest, especially if the respective Q95(10) values place the two catchments in the same section 3.4 category. In such a case one may apply the ungauged techniques of section 3.3 and 3.4 to obtain Q95, Q5 and ADF for the site of interest. These quantities would then be rescaled using the data-based values of MRV in equation 3.1 to yield a better estimate of the monthly flow duration curve.

4.3 Monthly data

Monthly data at or near the site of interest can be used to determine the monthly runoff volume, either in absolute or MRV terms. The weight that can be attached to the resulting figures will be dependent on the period of data available. This information can then be used in preference to Figures 3.6, 3.7 or Table 3.2 in section 3.4.

4.4 Current metering

Section 4 of Report 2.1 describes a method of using several current meterings at the site of interest in association with a known annual flow duration curve at a nearby gauged site to construct an annual flow duration curve at the required site. The technique is identical for a monthly or seasonal curve except that clearly the current meterings must all be made during the calendar months for which the curve is intended.

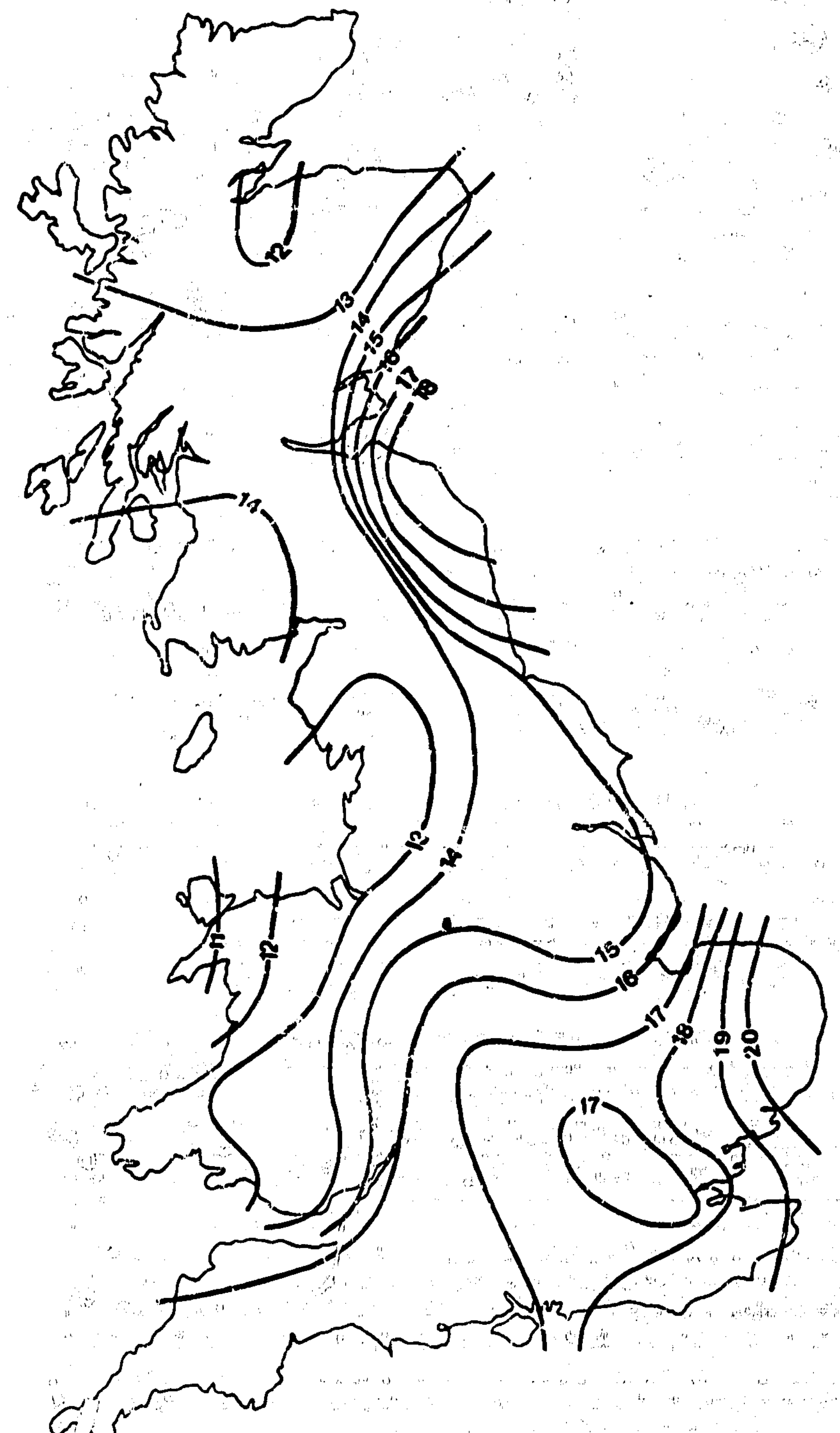

FIGURE 3.6 (JAN) PERCENT OF ANNUAL RUNOFF OCCURRING ON CATCHMENTS WITH 0% ADF Q95(10) < 15% ADF

FIGURE 3.6 (FEB) PERCENT OF ANNUAL RUNOFF OCCURRING ON CATCHMENTS WITH 0% ADF < Q95(10) < 15% ADF

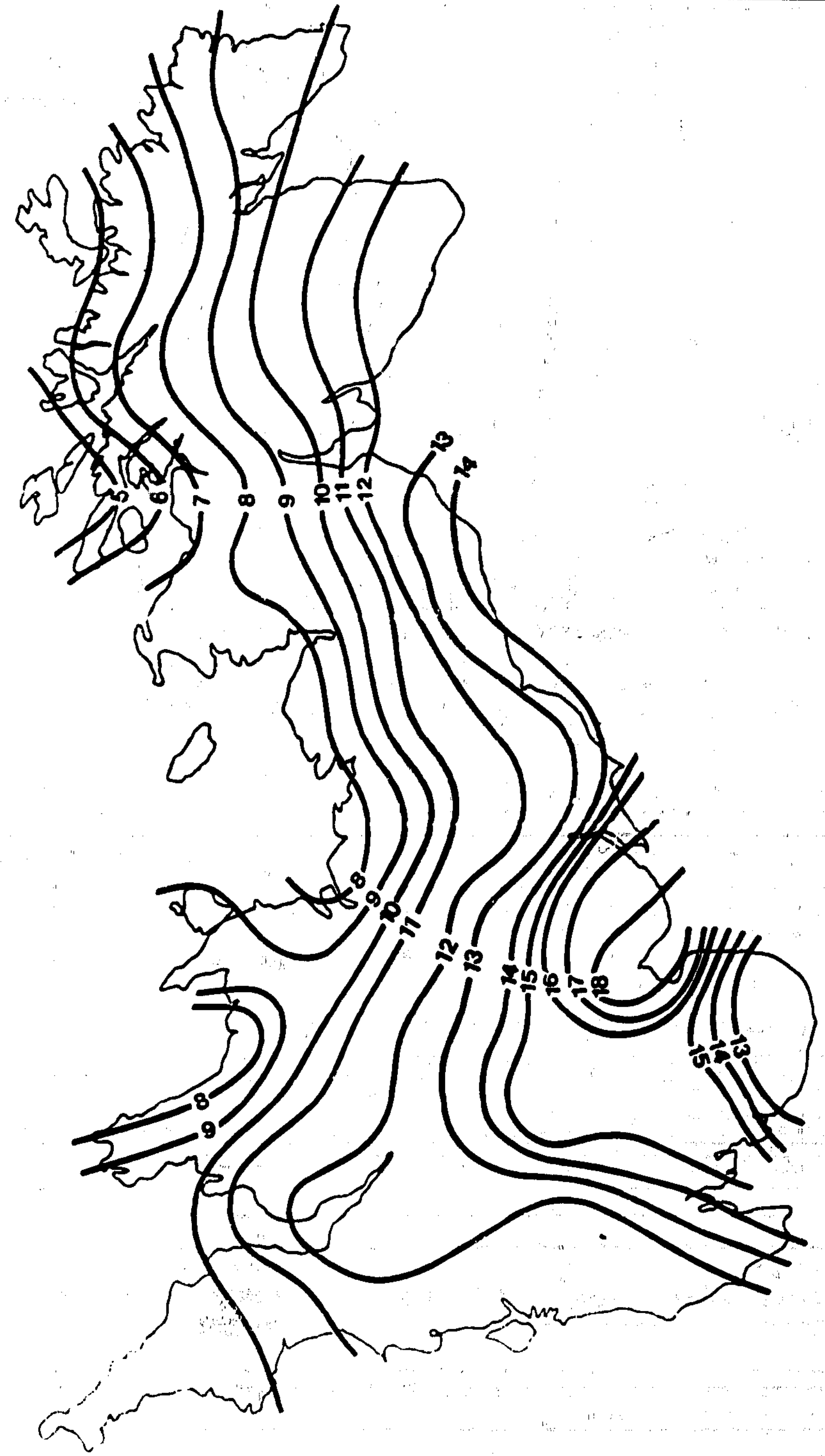

FIGURE 3.6 (MAR) PERCENT OF ANNUAL RUNOFF OCCURRING ON CATCHMENTS WITH 0% ADF < Q95(10) < 15% ADF

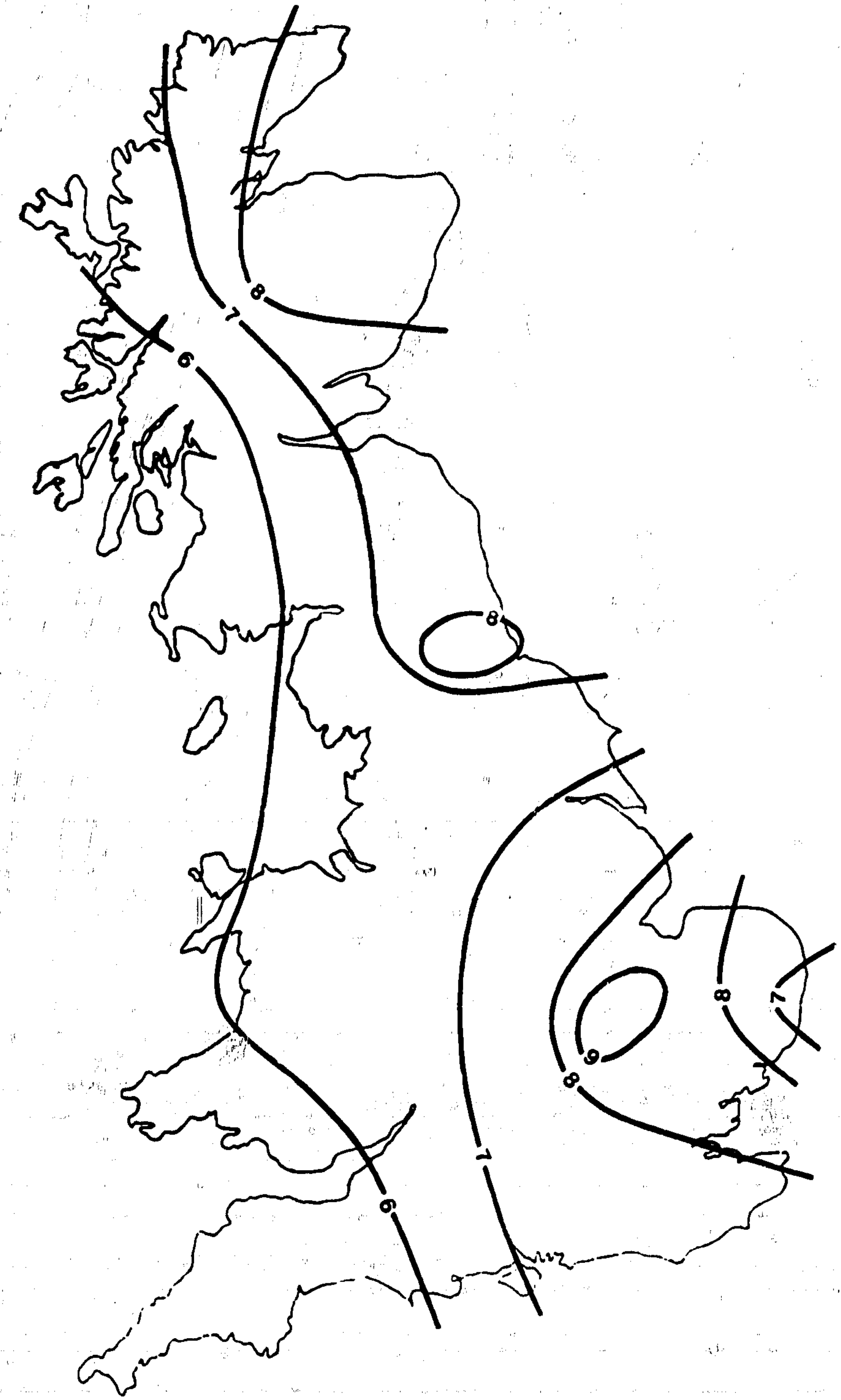

FIGURE 3.6 (APR) PERCENT OF ANNUAL RUNOFF OCCURRING ON CATCHMENTS WITH 0% ADF < Q95(10) < 15% ADF

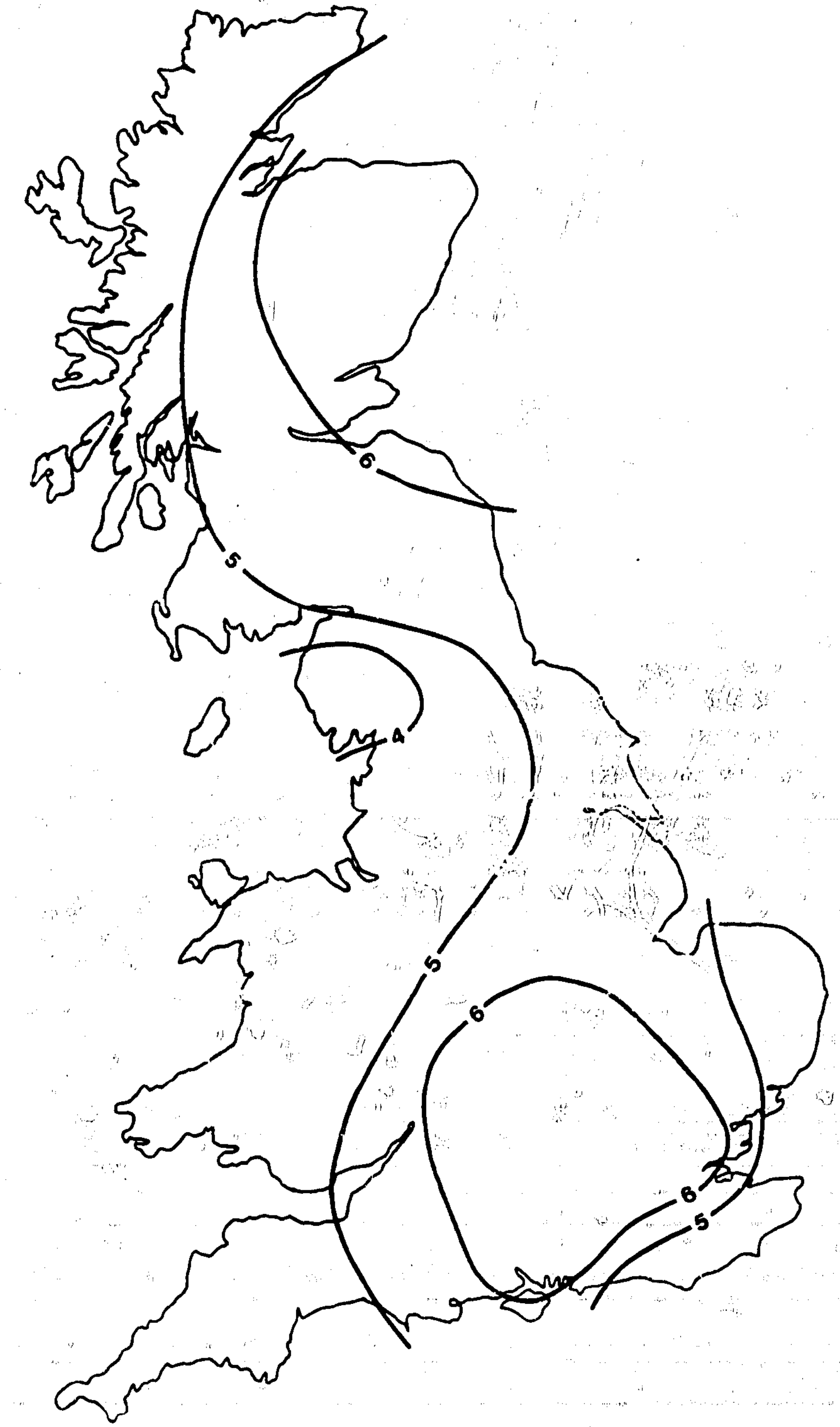

FIGURE 3.6 (MAY) PERCENT OF ANNUAL RUNOFF OCCURRING ON CATCHMENTS WITH 0% ADF < Q95(10) < 15% ADF

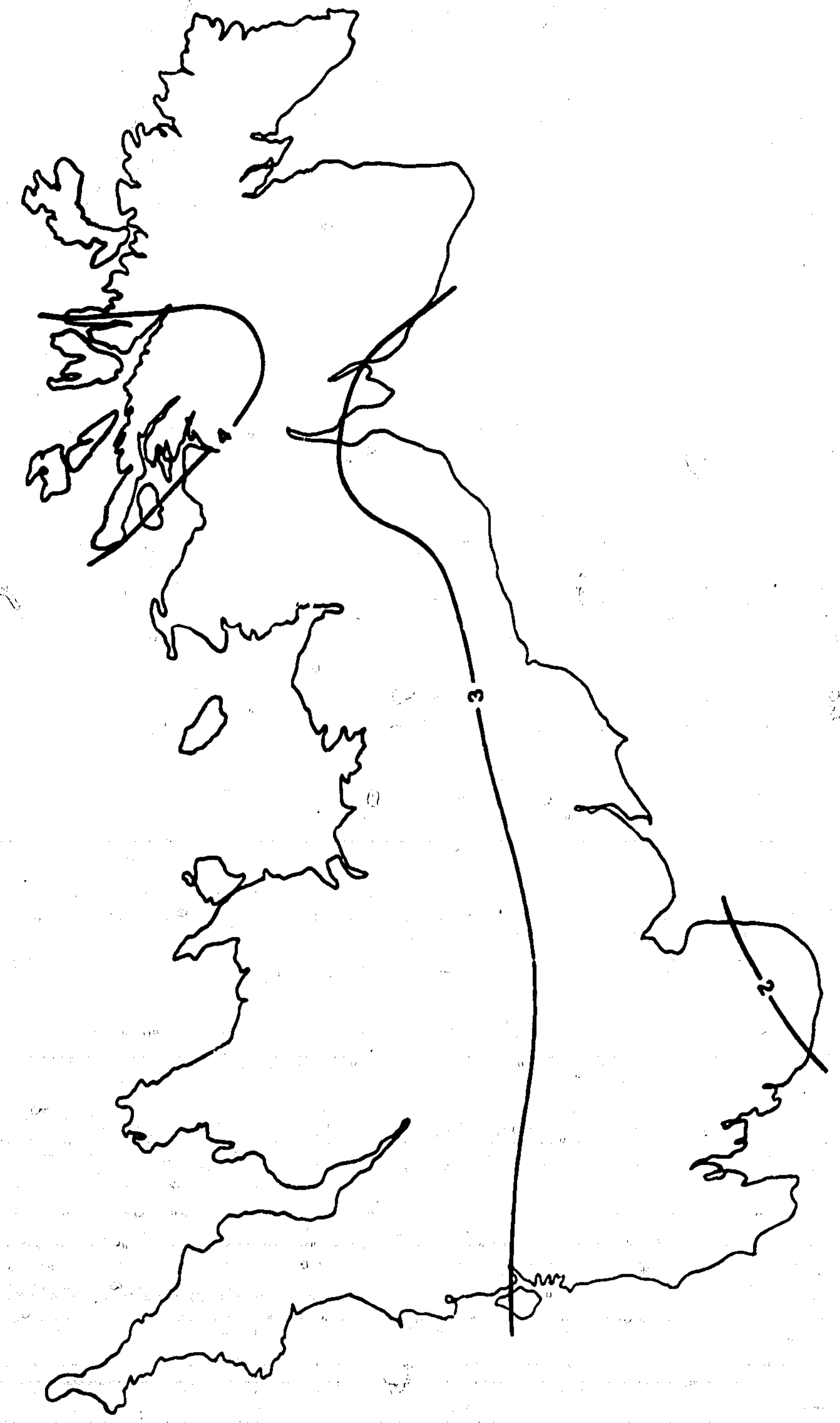

FIGURE 3.6 (JUN) PERCENT OF ANNUAL RUNOFF OCCURRING ON CATCHMENTS WITH 0% ADF < Q95(10) < 15% ADF

FIGURE 3.6 (JUL) PERCENT OF ANNUAL RUNOFF OCCURRING ON CATCHMENTS WITH 0% ADF < Q95(10) < 15% ADF

FIGURE 3.6 (AUG) PERCENT OF ANNUAL RUNOFF OCCURRING ON CATCHMENTS WITH 0% ADF < Q95(10) < 15% ADF

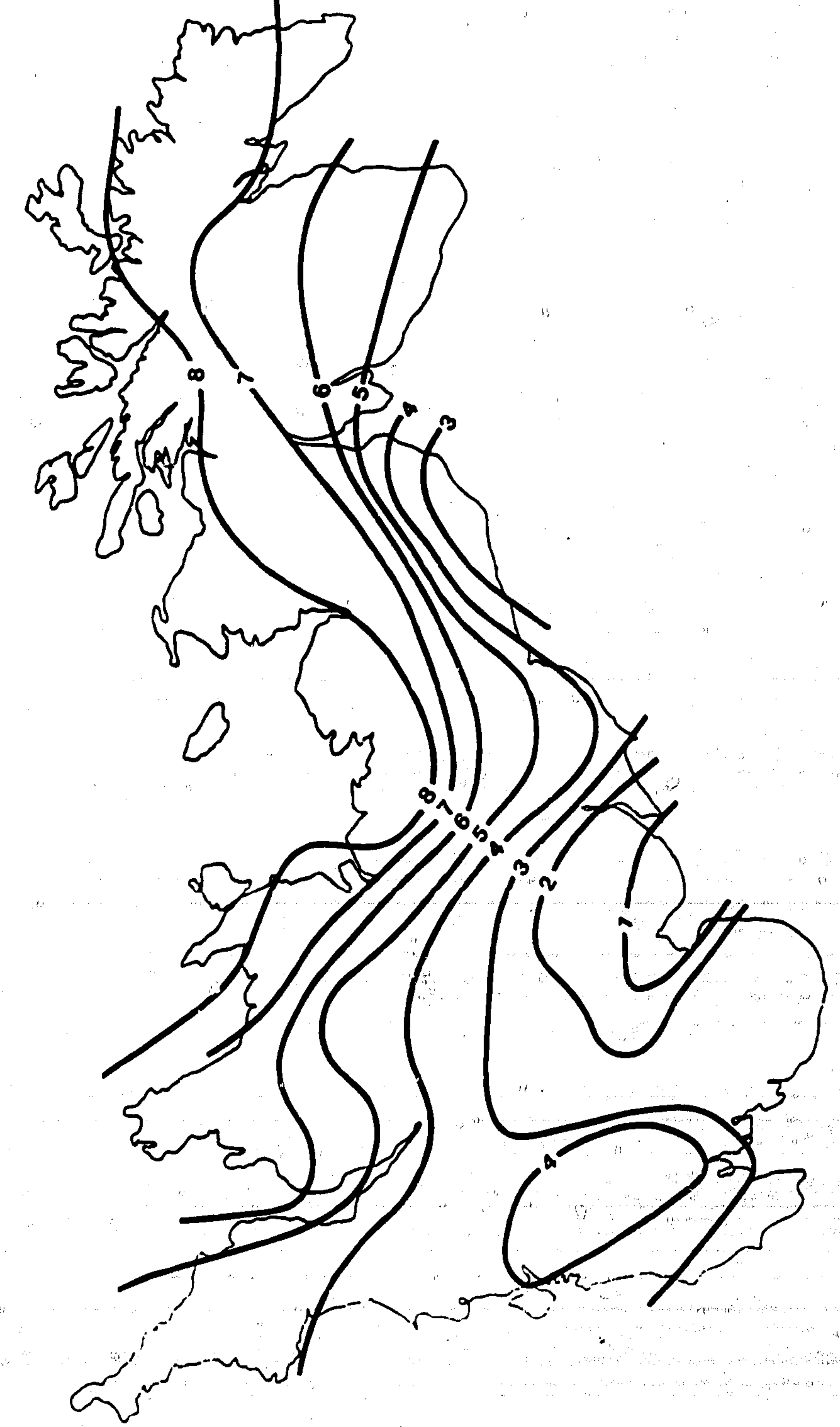

FIGURE 3.6 (SEPT) PERCENT OF ANNUAL RUNOFF OCCURRING ON CATCHMENTS WITH 0% ADF < Q95(10) < 15% ADF

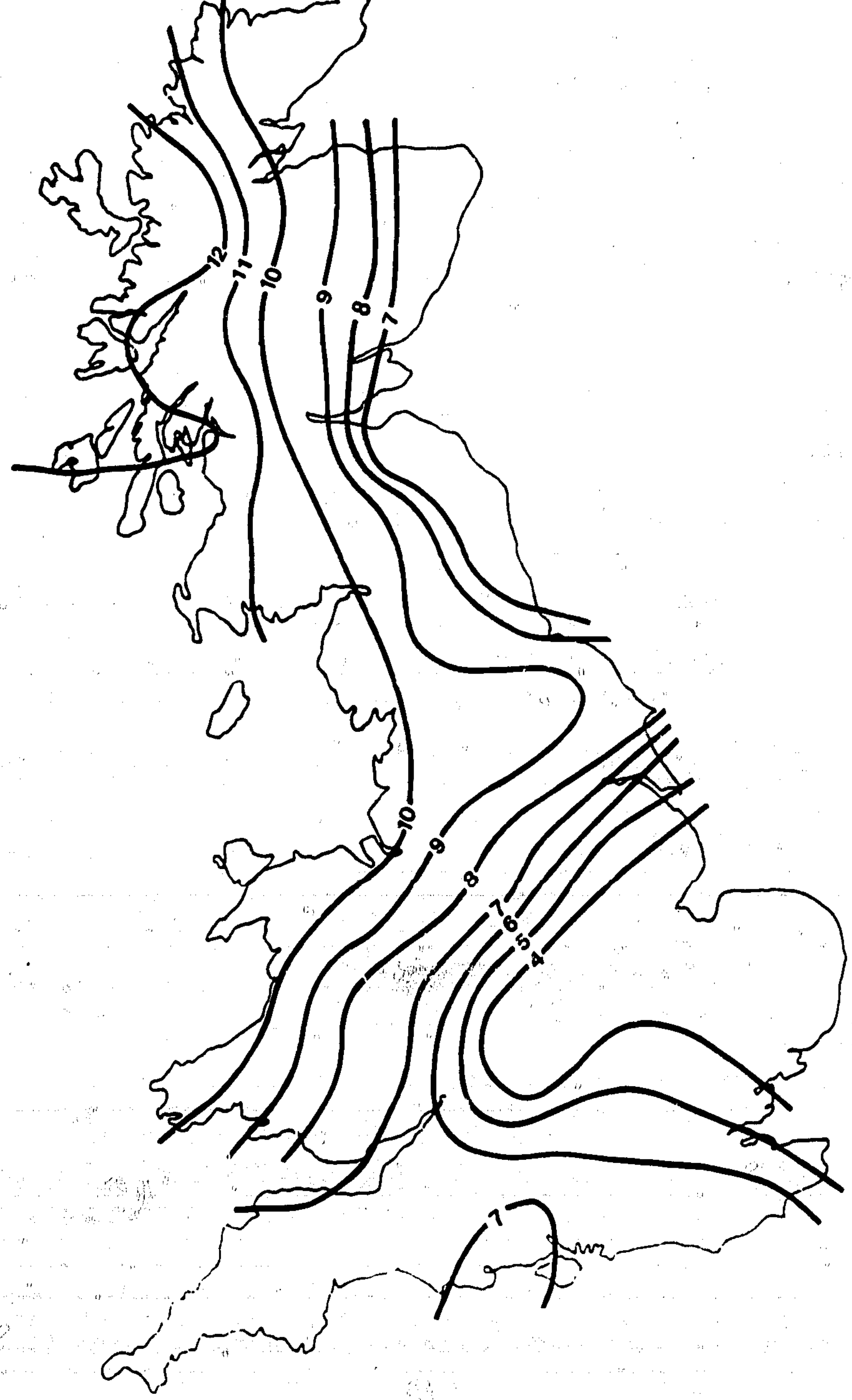

FIGURE 3.6 (OCT) PERCENT OF ANNUAL RUNOFF OCCURRING ON CATCHMENTS WITH
0% ADF < Q95(10) < 15% ADF

FIGURE 3.6 (NOV) PERCENT OF ANNUAL RUNOFF OCCURRING ON CATCHMENTS WITH
0% ADF < Q95(10) < 15% ADF

FIGURE 3.6 (DEC) PERCENT OF ANNUAL RUNOFF OCCURRING ON CATCHMENTS WITH
0% ADF ≤ Q95(10) < 15% ADF

FIGURE 3.7 (JAN) PERCENT OF ANNUAL RUNOFF OCCURRING ON CATCHMENTS WITH
15% ADF < Q95(10) < 30% ADF

FIGURE 3.7 (FEB) PERCENT OF ANNUAL RUNOFF OCCURRING ON CATCHMENTS WITH 15% ADF < Q95(10) < 30% ADF

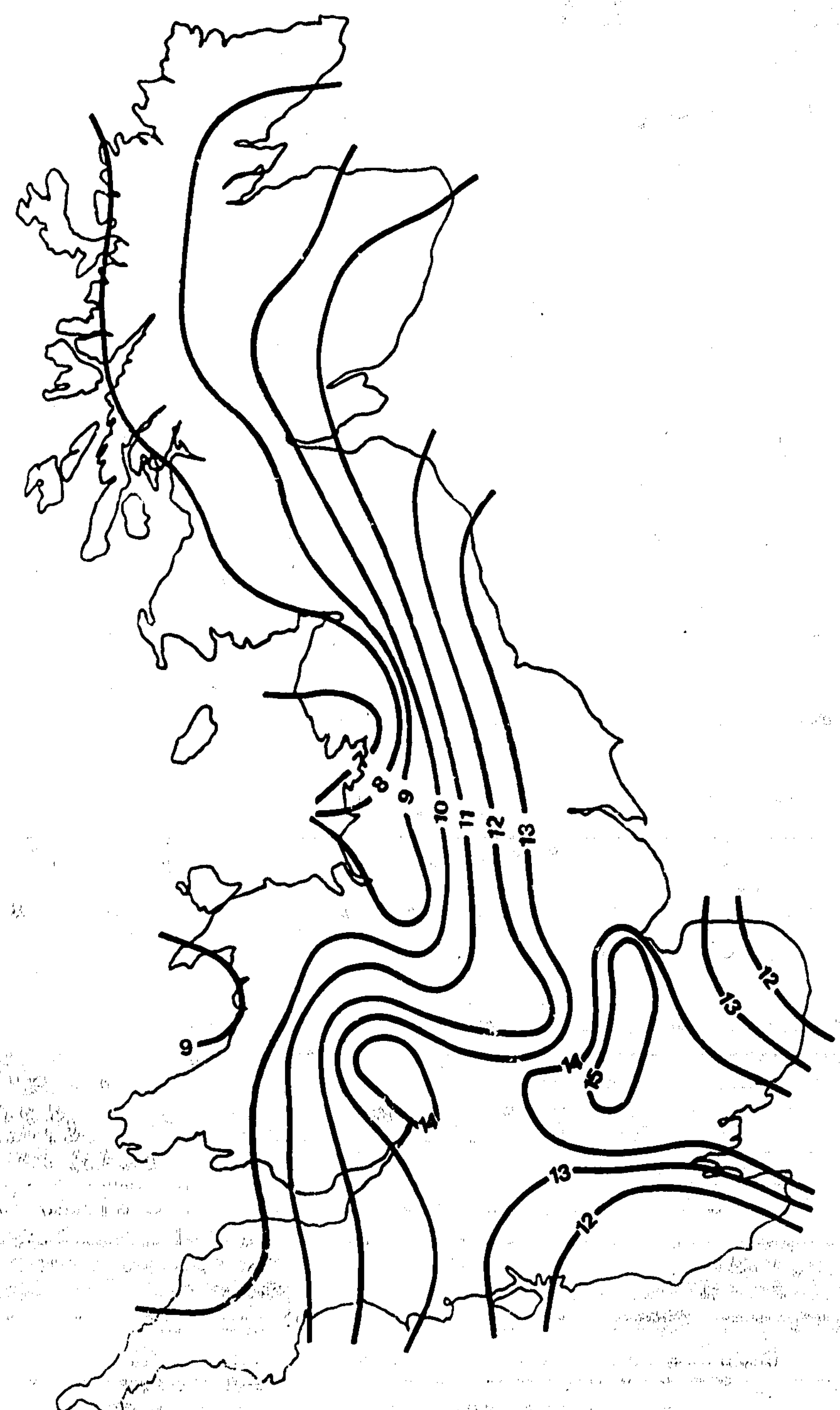

FIGURE 3.7 (MAR) PERCENT OF ANNUAL RUNOFF OCCURRING ON CATCHMENTS WITH 15% ADF < Q95(10) < 30% ADF

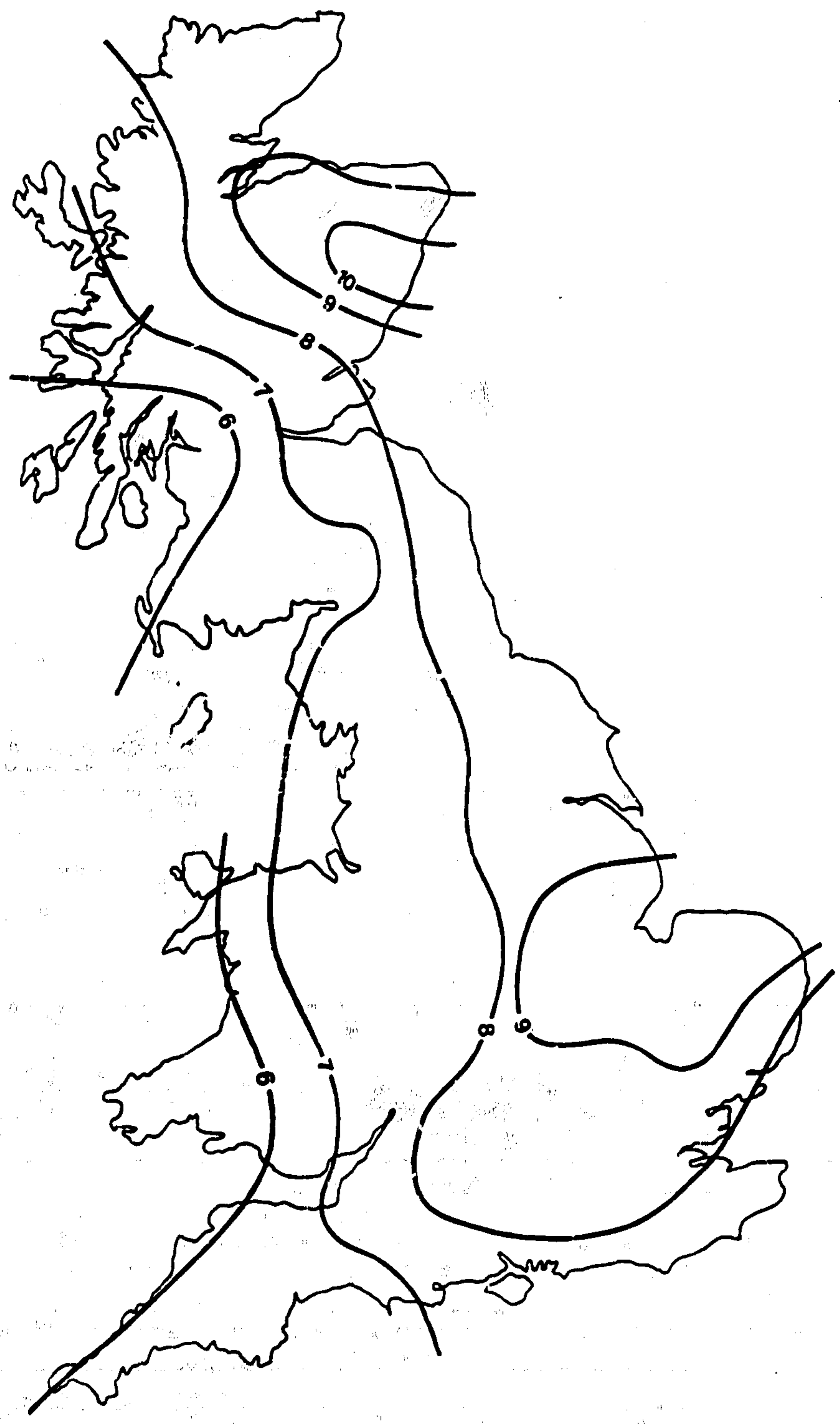

FIGURE 3.7 (APR) PERCENT OF ANNUAL RUNOFF OCCURRING ON CATCHMENTS WITH 15% ADF < Q95(10) < 30% ADF

FIGURE 3.7 (MAY) PERCENT OF ANNUAL RUNOFF OCCURRING ON CATCHMENTS WITH 15% ADF < Q95(10) < 30% ADF

FIGURE 3.7 (JUN) PERCENT OF ANNUAL RUNOFF OCCURRING ON CATCHMENTS WITH 15% ADF < Q95(10) < 30% ADF

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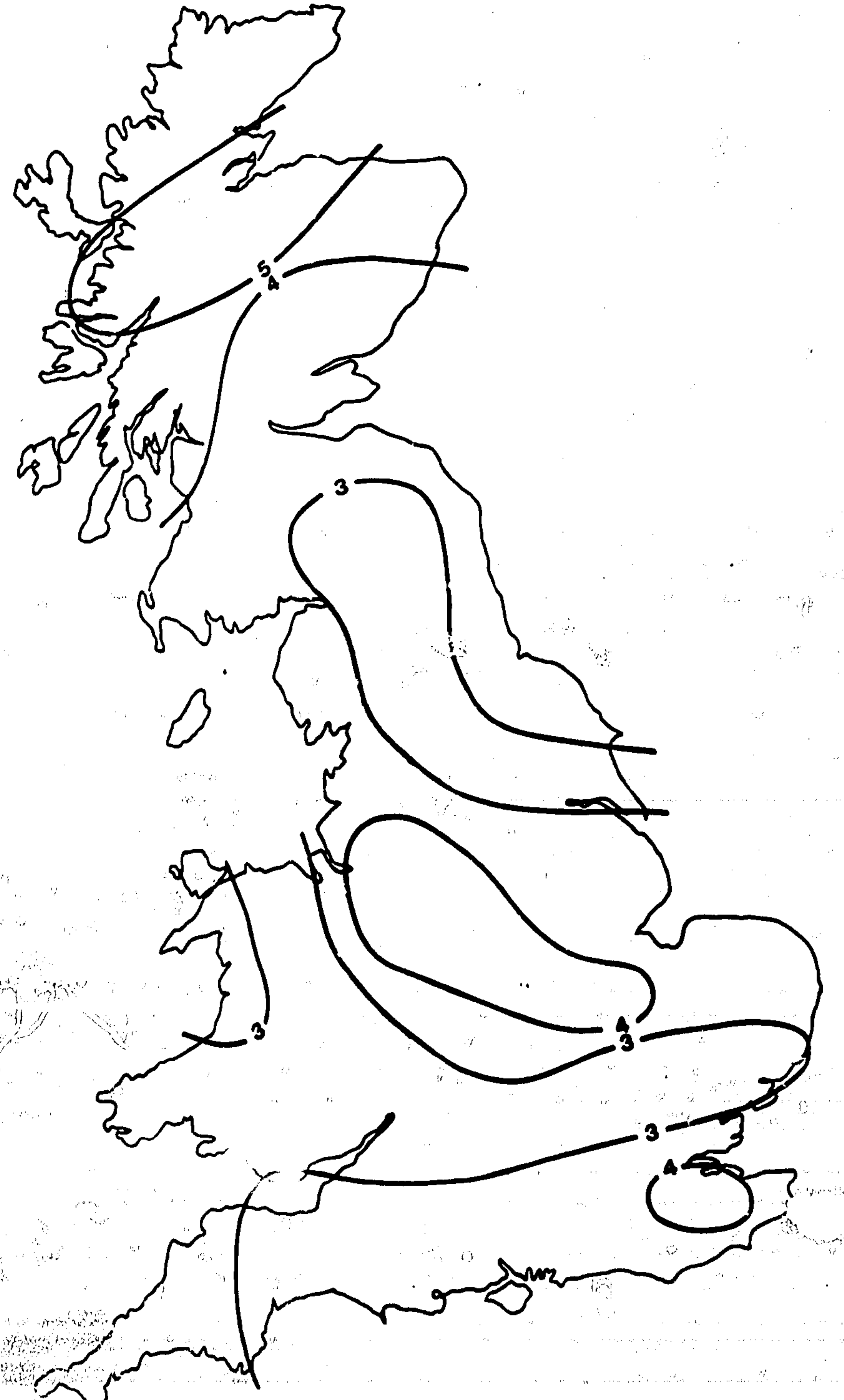

FIGURE 3.7 (JUL) PERCENT OF ANNUAL RUNOFF OCCURRING ON CATCHMENTS WITH 15% ADF < Q95(10) < 30% ADF

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FIGURE 3.7 (AUG) PERCENT OF ANNUAL RUNOFF OCCURRING ON CATCHMENTS WITH 15% ADF < Q95(10) < 30% ADF

FIGURE 3.7 (SEPT) PERCENT OF ANNUAL RUNOFF OCCURRING ON CATCHMENTS WITH 15% ADF < Q95(10) < 30% ADF

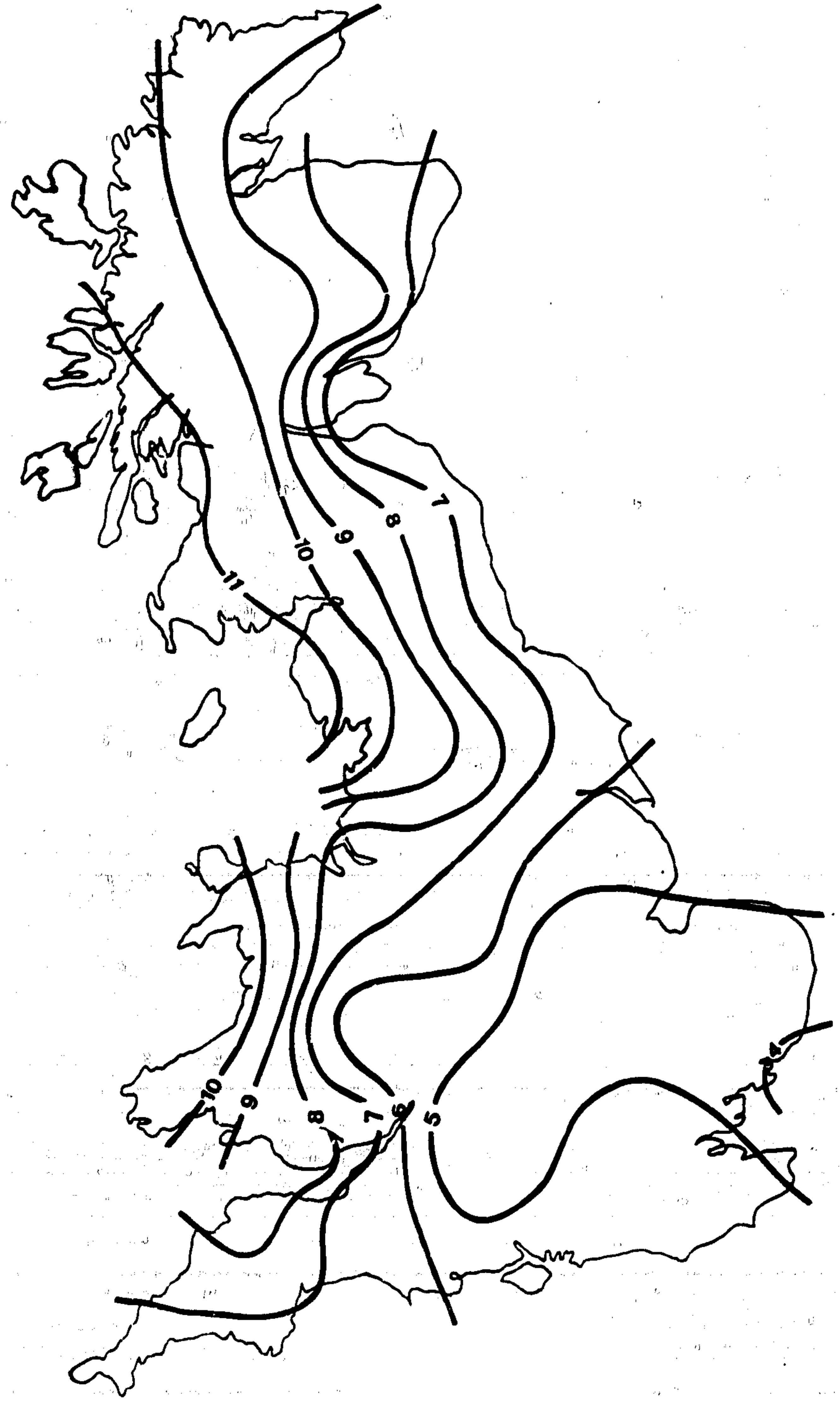

FIGURE 3.7 (OCT) PERCENT OF ANNUAL RUNOFF OCCURRING ON CATCHMENTS WITH
15% ADF < Q95(10) < 30% ADF

FIGURE 3.7 (NOV) PERCENT OF ANNUAL RUNOFF OCCURRING ON CATCHMENTS WITH
15% ADF < Q95(10) < 30% ADF

FIGURE 3.7 (DEC) PERCENT OF ANNUAL RUNOFF OCCURRING ON CATCHMENTS WITH 15% ADF < Q95(10) < 30% ADF